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The Chinese Meridian Project (CMP) and the International Meridian Circle Program (IMCP): Overview, Progress, and Achievements

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Abstract The National Major Scientific and Technological Infrastructure — the Chinese Meridian Project (CMP) — completed its Phase II acceptance and integration with Phases I in March 2025, and has since entered full operation. The project employs a detection architecture consisting of “one chain, three networks, and four focuses”, deploying 282 monitoring instruments across 31 stations within China’s territory and at both poles. This forms a grid-like comprehensive ground-based network monitoring the geospace environment along 100°E, 120°E, 30°N, and 40°N. Currently, this project has the world’s most extensive, comprehensive, and capable such network. The data it acquires are openly shared globally, supporting worldwide cutting-edge scientific research on space weather and its warning/forecasting. This article highlights research advances achieved over the past two years using the CMP data, and briefly introduces the International Meridian Circle Program, which is currently being promoted and initiated based on the CMP.

Key words Chinese Meridian Project, International Meridian Circle Program, Solar-interplanetary space, Ionosphere, Middle and upper atmosphere

Classified index P35

1 Overview of the Chinese Meridian Project

The Solar-terrestrial space serves as a natural laboratory for contemporary scientific exploration and the primary arena for human space activities and space development. Monitoring and research on the Solar-terrestrial space environment to understand its characteristics, reveal cascading processes and patterns of space weather changes, and improve forecasting capabilities is essential for humanity to enter and utilize space.

Monitoring of the Solar-terrestrial space environ-

ment can be carried out through two approaches: ground-based and space-based. Compared with space-based monitoring, ground-based monitoring offers the 5C advantages of being Continuous, Convenient, Controllable, Credible, and Cost-effective. Therefore, establishing ground-based space environment monitoring facilities in China, comprehensively conducting monitoring and research on complex and interlinked processes of the Solar-terrestrial space environment, and improving space weather forecasting capabilities are of great scientific significance and urgent demand. To meet this scientific and application demand, the Chinese Meridian

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Project (CMP) came into being.

The CMP is China's sole large research infrastructure dedicated to the observation and research of space weather. Through two phases of construction, it has deployed nearly 300 sets (or units) of monitoring equipment at 31 stations across China and the North and South Poles, forming a space environment monitoring network along two longitude lines (100°E and 120°E) and two latitude lines (40°N and 30°N)^[1,2]. This monitoring network deploys advanced solar-interplanetary instruments along the Solar-terrestrial space chain, enabling end-to-end monitoring from solar eruptions to Earth's response (one chain). It employs geomagnetic, radio, and optical detection methods to construct a networked detection system covering the ionosphere, middle and upper atmosphere, and geomagnetic field over China (three networks). In the polar high-latitude region, northern mid-latitudes, low latitudes around Hainan, and the Qinghai-Xizang Plateau, it has built a number of internationally advanced or leading large-scale instruments for fine-scale "microscopic" detection (four focuses). The "one chain, three networks, four focuses" architecture achieves, for the first time in the world, a comprehensive, three-dimensional, multi-element detection of the entire Solar-terrestrial space environment, elevating China's ground-based space environment detection and research to a world-leading level and playing a key role in advancing our understanding and forecasting capabilities in the Solar-terrestrial domain.

The CMP-Phase II successfully passed its process acceptance in June 2024 and received national acceptance in March 2025. This marks the completion of the entire Chinese Meridian Project construction. After nearly two years of trial operation and formal operation, the data acquired have been made openly accessible to scientists worldwide*. Over the past two years, nearly 300 papers have been published based on CMP data, demonstrating its significant and emerging benefits for research and applications in the Solar-terrestrial space environment. This paper systematically reviews the main achievements from 2024 to 2025 in key research areas such as solar and interplanetary physics, the ionosphere, and the middle and upper atmosphere, all derived from CMP data. Additionally, it briefly introduces the Interna-

tional Meridian Circle Program, a major international initiative being advanced based on the CMP.

2 Major Research Achievements of CMP over the Past Two Years

2.1 Observation and Research of the Solar and Interplanetary Space

Based on Phase I, CMP-Phase II added a solar-interplanetary monitoring chain, deploying equipment such as solar radio and interplanetary scintillation monitors, thereby providing rich observational data support for the project's observation of solar activity eruptions and their geoeffectiveness.

The solar radio spectrum system (CBSm) built at Chashan, Rongcheng Station provides radio spectrum observations for studying the radiation mechanisms of solar eruptions. Using CBSm data, Li *et al.*^[3] discovered a novel fine spectral structure in solar radio emission termed as "periodic beaded stripes". Based on the double plasma resonance instability and modulation by low-frequency MHD waves, they proposed a physical model that explains this new phenomenon and can be used to diagnose key parameters such as the source density and magnetic field. Yang *et al.*^[4] automatically identified and statistically analyzed more than 105 Type I bursts. Lifetimes, bandwidths, polarization properties, and sub-second periodicities within burst chains were systematically characterized, yielding new constraints on the particle acceleration and radiation mechanisms underlying Type I bursts. In addition, Cui *et al.*^[5] investigated a Type II burst without an accompanying CME. They found that the jet-induced disturbance evolved into a shock wave in a coronal loop with low Alfvén speed, which further drove the Type II burst and the associated Type III/N bursts, revealing a new mechanism for high-frequency Type II bursts under weak-activity conditions.

The IPS telescope is a pivotal interplanetary monitoring device within the Solar-terrestrial monitoring chain of the CMP. It is China's first IPS observation-dedicated facility and currently the world's largest in aperture. Recently, researchers have made significant progress in hardware-software integration and first-light detection using this instrument. Fan *et al.*^[6] employed

* <https://www.meridianproject.ac.cn/en/>

PANDA, a diffusion model-based generative AI calibration method, to control the digital-analog hybrid beam-forming architecture, enabling phased array feed calibration under variable radio frequency interference. Xiong *et al.*^[7] used the telescope to detect dual-polarization IPS signals from the radio source 3 C446 and derive the solar wind speed, enabling remote sensing of the solar wind speed at 24 solar radii.

2.2 Observation and Research of the Ionosphere

2.2.1 Study of Ionospheric Response to Extreme Geomagnetic Storms

The years 2024 and 2025 are right at the peak of the 25th solar activity cycle. The continuous, multi-instrument, and large-scale monitoring of the CMP provides favorable means for studying the response mechanisms of the ionosphere to intense eruptive solar activities.

Flares are among the most violent activity phenomena on the Sun, accompanied by suddenly enhanced X-ray and Extreme Ultraviolet (EUV) radiation. Recent studies have shown that in some flares, the EUV radiation increases again during the late phase, a phenomenon referred to as the EUV late phase of solar flares. Based on multi-source ionospheric and geomagnetic observation data from the CMP and other facilities, as well as results from the TIEGCM driven by realistic solar radiation spectra, Liu *et al.*^[8] provided the first direct evidence that the flare late phase significantly affects ionospheric electron density. Liu *et al.*^[9] further utilized data from more than 200 geomagnetic observatories worldwide, combined with simulation results, and found that the EUV late phase of flares can influence the ionospheric current system.

Geomagnetic storms are dramatic disturbances in the Earth's space environment triggered by solar eruptions. The super geomagnetic storm of May 2024 was the most intense geomagnetic storm in nearly two decades, injecting a large amount of solar wind and magnetospheric energy into the Earth's atmosphere and causing severe disturbances in the ionospheric environment. For this event, Chen *et al.*^[10] reported unprecedented observational evidence of extreme ionospheric electron density depletion and its hemispheric asymmetry, and confirmed that the negative ionospheric storm led to HF signal interruption. Their analysis showed that changes in neutral composition and disturbance electric

fields jointly caused the sharp electron density depletion, while neutral winds from the summer hemisphere to the winter hemisphere, together with the asymmetry in the neutral composition ratio (O/N_2), were the main reasons for the north-south asymmetry. In addition, researchers have investigated various ionospheric changes and irregularities of different scales during multiple geomagnetic storms, including: mid-latitude density enhancement structures^[11], storm-time east-west asymmetric responses^[12], super plasma bubbles^[13,14], nighttime ionospheric enhancements^[15,16], and storm-time thermospheric temperature changes^[17,18]. These studies reveal the diversity and complexity of the ionospheric response to solar activity, and provide support for a deeper understanding of how solar activity drives different types of ionospheric variations.

2.2.2 Study of Ionospheric Irregularities in Mid- and High-latitude Regions

The polar region is the main area where solar wind mass and energy are injected into Earth's space. Studying the solar wind-magnetosphere-ionosphere coupling processes in the polar region under different interplanetary conditions is of great significance for both fundamental research and forecasting applications in space weather. Traditional understanding holds that under northward IMF conditions, the energy coupling efficiency is very low. Zhang *et al.*^[19] discovered a typhoon-like phenomenon above the ionosphere around the Earth's north geomagnetic pole under extremely quiet geomagnetic conditions, and named it as "space hurricane". They found that the space hurricane is a huge funnel-shaped magnetic spiral structure generated by a stable high-latitude lobe reconnection and current continuity. By accelerating polar ionospheric plasma upwelling and electron precipitation into the ionosphere, it opens a huge and rapid energy transfer channel between the solar wind and the magnetosphere. Lu *et al.*^[20] and Xiu *et al.*^[21] revealed for the first time that the space hurricane is accompanied by enhanced convection electric fields and Joule heating, which heats the local ionosphere/thermosphere, drives ion upwelling, and disturbs the polar thermosphere to excite gravity waves. Lu *et al.*^[22] further confirmed the lobe reconnection mechanism of the space hurricane by statistically analyzing its occurrence frequency, temporal and spatial distribution characteristics,

and plasma properties in the Southern Hemisphere.

The mid-latitude ionosphere connects the polar and low-latitude ionospheres and serves as an important region for coupling and disturbance propagation between high, middle, and low latitudes, where the ionospheric dynamic processes are particularly complex. The Chinese Dual Auroral Radar Network (CN-DARN) of the CMP enables continuous monitoring of the ionospheric environment over Asian middle and high latitudes, covering 40°N–80°N, extending more than 4000 km northward and spanning over 10000 km east-west, providing new opportunities for studying ionospheric disturbances in this region. Based on continuous observations from CN-DARN, Zhang *et al.*^[23] found that CN-DARN completely captured the rare spatiotemporal evolution process of dawnside Subauroral Polarization Streams (SAPS), and revealed a direct physical connection between the dawnside SAPS acceleration and auroral intensification. They also determined that, during intense geomagnetic storms, high-speed ionospheric irregularities induced by the dawnside SAPS can intrude into Chinese airspace and disturb the stability of the regional ionospheric environment. In addition, they quantified the impact of auroral activity on high-frequency communication in the Asian region. Using a total of 12 high-frequency radars, including the CN-DARN radars and six international SuperDARN radars, Zhao *et al.*^[24] successfully achieved simultaneous, large-scale, high-spatiotemporal-resolution observations of two types of SAPS on both the dusk side and the dawn side during an intense geomagnetic storm. They clarified the key differences between the two types of SAPS in terms of spatial distribution, temporal evolution, and formation conditions.

2.2.3 Study of Ionosphere in Low-latitude Regions

Due to the complex structures such as ionospheric irregularities and the equatorial anomaly, as well as rich dynamic and electrodynamic processes, the low-latitude region is one of the areas where severe space weather phenomena occur most frequently on Earth, and it is also a region of strong thermosphere-ionosphere coupling. The low-latitude ionospheric environment can significantly affect various high-technology systems, including satellite communication and navigation, making it a key area of focus for international space environment observation and research in recent years. The CMP has de-

ployed a series of observational instruments in the low-latitude region of Hainan, China, including radio radars, lidars, and magnetometers, providing strong data support for ionospheric research in this region.

The CMP has built an incoherent scatter radar in Hainan, which is the only phased-array ISR currently operational at low latitudes. Researchers have used this facility to conduct research on the dynamics of the low-latitude ionosphere over Hainan. Zhang *et al.*^[25] developed a sophisticated algorithm to derive neutral wind and electric field from multiple beams SYISR measurements, providing a new data source for studies of ionospheric dynamics and low-latitude atmosphere-ionosphere-magnetosphere coupling. Yue *et al.*^[26] observed the 150-km echo anomaly in the UHF band for the first time; Xu *et al.*^[27] and Zhao *et al.*^[28] obtained the vertical characteristics of Large-Scale Traveling Ionospheric Disturbances (LSTIDs) and ionospheric holes triggered by rocket launches, respectively. These efforts will provide an important observational basis for studying the regional characteristics of the ionosphere over East Asia.

Equatorial Plasma Bubbles (EPBs) are common irregular structures in low-latitude regions, containing various small- and medium-scale field-aligned irregularities. These irregular structures interfere with radio wave propagation applications, adversely affecting communications, navigation, and other systems. Using observations from the CMP, researchers have conducted studies on the large-scale characteristics of plasma bubbles in low-latitude regions, the evolution of bubble structural features, and the fine structures within bubbles, achieving a series of breakthroughs. Hu *et al.*^[29], using Low Latitude long Range Ionospheric raDar (LARID), for the first time depicted a complete picture of EPB originating over the Indian Ocean and then drifting and evolving over a large east-west extent to influence the South China Sea. Sun *et al.*^[30], through comprehensive observational studies of plasma bubble events during several magnetic storms, presented the large-scale spatial distribution characteristics of super plasma bubbles extending to mid-latitudes, discussed their controlling factors, and revealed the promoting effect of rapid penetration electric fields accompanying the southward turning of the IMF B_z component during storms on super plasma bubble events. Jia *et al.*^[31] revealed the distribution and

maintenance mechanisms of small- and medium-scale irregularities within plasma bubbles in the different dissipation phases; Jia *et al.*^[32] explored the mechanism by which irregularities extend outside the bubbles and confirmed the existence of inter-bubble electrostatic reconnection. By comprehensively utilizing observations from the CMP's calcium ion lidar and radio radar, Sun *et al.*^[33] captured for the first time the depletion and bifurcation structures of EPBs, surpassing the detection limits of conventional radars and demonstrating that metal ions can serve as a “developer” for EPBs, providing a new means to study the mapping process of EPBs along magnetic field lines.

2.3 Observation and Research of the Middle and Upper Atmosphere

The middle and upper atmosphere is a key transition region from Earth's atmosphere to space. Solar activity has a significant impact on the middle and upper atmosphere. Meanwhile, through complex coupling processes among different atmospheric layers, activities in the lower atmosphere or the lithosphere can also drive environmental changes in the middle and upper atmosphere and the ionosphere. Key scientific issues such as the effects of space weather events on the middle and upper atmosphere, the coupling between the upper and lower atmospheres, and the latitudinal and longitudinal transmission of energy and momentum represent frontier directions in current basic space physics research.

Leveraging the observational network of the CMP, researchers have conducted in-depth studies on anomalous changes in the neutral atmosphere of the Mesosphere and Lower Thermosphere (MLT) region, the middle and upper atmosphere, and the ionospheric structure during typical space weather events. Using MST radar observations from the CMP's Wuhan and Beijing stations, Li *et al.*^[34] found for the first-time direct evidence that substorm events affect the atmospheric wind field in the mid-latitude MLT region through Joule heating, extending the influence of geomagnetic activity on geospace to the mid-latitude lower thermosphere. Additionally, Chen *et al.*^[35] discovered for the first time that the solar eclipse can trigger an intermediate descending layer, revealing the complex dynamic processes and their coupling effects in the geospace environment during an eclipse. Hu *et al.*^[36] observed rare large-scale

stripe-shaped irregularities and found that MSTIDs (Medium-Scale Traveling Ionospheric Disturbances) lead to the generation of field-aligned irregularities in the low-latitude F region, indicating that equatorial plasma bubbles are not the only source of field-aligned irregularities in the low-latitude F region.

In the middle and upper atmosphere, tides and gravity waves are important atmospheric wave phenomena, serving as key mediators for cross-layer coupling between the lower atmosphere and the middle/upper atmosphere. Using the CMP's meteor radar chain, Wang *et al.*^[37] investigated the Quasi-Biennial Oscillation (QBO) disruption. Their results suggest that the QBO wind affects mid-latitude mesospheric diurnal tides by modulating both the solar radiative absorption by subtropical stratospheric ozone and the tidal-gravity wave interaction in the mesosphere. Wang *et al.*^[38] analyzed the effects of topography differences (plateau vs. coastal terrain) at similar latitudes on gravity wave activity, finding that the seasonal variations in gravity wave activity over Kunming and Sanya/Fuke may be related to the unique surface wind patterns over Kunming and the convective systems over the Qinghai-Xizang Plateau. Based on observations from the CMP's airglow imager network, Li *et al.*^[39] for the first time observed a large-scale, long-distance propagating mode of atmospheric gravity waves, which were generated by the interaction between tsunamis (triggered by the Tonga volcanic eruption) and the atmosphere. Combining meteor radar data from the CMP's Mohe station and Germany's Collm station, He *et al.*^[40,41] analyzed nine years of atmospheric wind observations in the meteor layer. They identified for the first time higher-order solar-synchronous tides with periods of 4.8 hours and 4 hours, clarified that multi-day disturbances are primarily driven by atmospheric normal modes with their dynamic mechanisms significantly influenced by seasonal factors, and revealed non-linear interactions among more than ten normal modes as well as between normal modes and tides. These interactions promote the transfer and dissipation of energy from planetary to smaller scales. Collectively, these findings demonstrate that variations in the mesosphere can be linked to changes in the troposphere/stratosphere lower atmosphere *via* atmospheric waves such as tides and gravity waves, providing new insights into the cou-

pling between the lower and middle/upper atmospheres.

2.4 Research Progress in Space Weather

Forecasting

The completion of the CMP has, on the one hand, facilitated major breakthroughs in original scientific research, and on the other hand, provided valuable observational data for the development of space environment forecasting technology.

The spatiotemporal variation of ionospheric Total Electron Content (TEC) is extremely complex, and its prediction is of great significance for the accuracy and stability of radio communication, navigation, positioning, and related applications. Using ionospheric GNSS observation data from the CMP, Yang *et al.*^[42] developed a Convolution Long Short-term Memory (ConvLSTM) network model for TEC forecasting (with a spatial resolution of $5^{\circ} \times 2.5^{\circ}$ (longitude $\times$ latitude) and a time resolution of 1 h). Performance evaluation results show that the model achieves average Root Mean Square Errors (RMSE) of 2.81, 3.16, and 3.41 TECU for 1-day, 2-day, and 3-day TEC forecasts, respectively, demonstrating a significant improvement in performance compared to the 1-day forecast product of the IRI-Plas model.

Ionospheric scintillation, a phenomenon of radio signal fluctuation caused by ionospheric irregularities, can significantly reduce the accuracy and stability of navigation systems. Therefore, establishing accurate and effective ionospheric scintillation prediction models is of great importance for improving the reliability of navigation and communication systems. Gao *et al.*^[43] proposed an ionospheric scintillation prediction method based on a dynamic spatiotemporal decomposition framework. This method can predict the distribution of the ionospheric scintillation index in low-latitude regions reasonably accurately one hour in advance. Its flexible dynamic modeling framework and extensibility for external variables can serve as a reference for modeling complex dynamic systems in other space weather events.

When a solar storm strikes Earth, the violently disturbed geomagnetic field induces geoelectric potentials on the Earth's surface, which in turn generate Geomagnetically Induced Currents (GIC) in ground-based power grids, threatening the safe operation of power systems. It is generally believed that high-latitude regions face a higher risk of GIC damage to power grids due to intense geomagnetic disturbances. In recent years, as the geo-

magnetic latitude of China has increased, assessing the impact of GIC on China's regional power grids has become increasingly important. Wang *et al.*^[44] studied the characteristics of geomagnetic field responses over China during the strong "Mother's Day" geomagnetic storm in 2024 and used a GIC model to evaluate the potential impact of this storm on the power grid in eastern Inner Mongolia. The results show that the intensity of this geomagnetic storm exceeded that of the November 2004 geomagnetic storm and was comparable to the March 1989 event. This work clearly reveals the disturbance characteristics of strong geomagnetic storm events on the geomagnetic field over China and their impact mechanism on the eastern Inner Mongolia power grid, fully demonstrating the large-area monitoring capability of the CMP and providing important scientific support for future geomagnetic storm risk assessment and extreme space weather protection.

2.5 Joint Observation and Research with Other Large-scale Scientific Facilities

Water ice, one of the most important resources on the Moon, exists in the polar regions, and detecting water ice in the lunar polar regions is a current hot topic in lunar research. Previous studies have indicated the presence of water ice in permanently shadowed regions of the lunar south pole using various methods; however, questions regarding the content, distribution, and form of water ice remain unresolved. Li *et al.*^[45] innovatively utilized the CMP's SYISR (Sanya Incoherent Scatter Radar) and the Five-hundred-meter Aperture Spherical radio Telescope (FAST) to form a ground-based bistatic radar system, obtaining circular polarization ratio radar images of the lunar south pole. By combining multi-source data, they estimated the upper limit of water ice content and its potential distribution in the lunar south polar region. The upper limit and distribution obtained in this study provide important information for research on the evolution of lunar water ice and can serve as a reference for selecting landing sites for future missions aimed at collecting water ice from the lunar south pole.

3 International Meridian Circle Program

Building upon the solid foundation of the Chinese

Meridian Project, China, in partnership with global collaborators, has initiated the International Meridian Circle Program (IMCP)^[46,47]. The IMCP aims to establish a globally distributed network of ground-based instruments—primarily along the 120°E and 60°W meridians—spanning multiple countries and continents, which will operate for at least a full solar cycle (11 years). By combining space-based observations, the IMCP will unravel the top-down and bottom-up mechanisms through which solar energy and terrestrial activity transfer into and disperse within geospace. Furthermore, the program will develop data-driven space weather models and high-precision forecasting products, providing a critical scientific basis for mitigating space weather disasters and promoting the peaceful utilization of space^[48].

Looking ahead to the next solar cycle and beyond, the IMCP will establish an international scientific organization headquartered in Beijing to guide and coordinate global activities across four core pillars^[49]. First, it will enhance global space weather monitoring by expanding the ground-based network through the establishment of key observatories and extending coverage to the 30°E and 150°W meridian chains, thereby enabling 24/7 solar eruption tracking, geospace-atmosphere coupling monitoring, and interdisciplinary solid Earth observations. Second, the organization will advance interdisciplinary research to investigate the solar drivers of space weather, energy coupling mechanisms, global and regional geospace characteristics, and the impacts of lithosphere-atmosphere processes, while pioneering next-generation space weather models and AI-driven forecasting. Third, it will establish a globally distributed data platform to integrate and standardize data streams from thousands of heterogeneous instruments worldwide, fostering open-data sharing. Finally, the program aims to cultivate a multi-layered global collaboration network by launching the open-access journal *Space Plus*, initiating joint research initiatives, and organizing international academic workshops and schools.

Ultimately, the IMCP represents a paradigm shift in heliophysics, leveraging unprecedented international cooperation to address global space weather challenges and answer the fundamental questions governing the solar-terrestrial coupling system.

Conflict of Interests The authors declare that there is no conflict of interests

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