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Research Advances of the Chinese Meridian Project in 2020–2021

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Abstract The Chinese Meridian Project (CMP) is a major national science and technology infrastructure invested and constructed by the Chinese government. The project builds space environment observation stations, focusing on the monitoring of the space environment over China, so as to provide a monitoring basis for clarifying the regional characteristics of the space environment over China and its relationship with global change, and making important innovative scientific achievements. The first phase of the CMP passed the national acceptance in 2012. It has been running for nearly ten years and has accumulated more than 8 TB monitoring data. These data are all available to all data users through the data center of the project. From 2020 to 2021, users of CMP data have completed a series of original works, which have solved current scientific problems in the field of space physics research. On the other hand, they also make us look forward to the completion of the second phase of CMP and its application benefits in national major strategic needs and cutting-edge scientific research.

Key words Chinese Meridian Project (CMP), Space physics, Magnetosphere, Ionosphere, Middle and upper atmosphere

Classified index P35

1 Overview of the Project

The Chinese Meridian Project (CMP) is a large-scale scientific facility funded by the Chinese government. The project is a joint effort of more than 10 institutions or universities in China, led by the National Space Science Center of Chinese Academy of Sciences. It is scheduled to be constructed in two phases. The first phase was under construction from 2008 to 2012 and has been in operation since 2012. The second phase was launched in 2019, and is expected to be completed by December 2023.

The first phase of CMP includes 15 ground-based observatories located roughly along the 120°E longitude and 30°N latitude. The longitudinal chain of observational stations starts from Mohe, the top north city of China. It runs south roughly through Beijing, Wuhan, Hainan within Chinese territory, and extends to China's Zhongshan station in the Antarctica. The latitudinal chain is constructed roughly following 30°N, spanning from Lhasa to Shanghai. 87 sets of monitoring instruments have been deployed at these stations to monitor the solar-terrestrial coupling and its influence on our planetary environment. Instruments include magnetometers, MST radar sets, meteor radar sets, high-frequency backscatter radar sets, incoherent scatter radar sets, traditional and digital ionosondes, lidars, Fabry-Perot interferometers, aurora spectrographs, *etc*.

Since 2012, the first phase of CMP has been run for ten years. It has continuously obtained more than 8 TB monitoring data of China's space environment near 120°E and 30°N, and has made a series of original scientific achievements in space physics and space weather. This article mainly presents the research highlights of the past two years.

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2 Major Scientific Achievements in 2020 and 2021

2.1 Study on Middle and Upper Atmosphere

2.1.1 Observations of Middle and Upper Atmosphere by Lidars

The first phase of CMP has deployed a Rayleigh-Sodium lidar chain near 120°E. The lidar chain of CMP provides scientists with a good tool to investigate the new features of the troposphere and the metal layers in the MLT region.

Cheng *et al.*[1] observed 20 occasions of falling mixed-phase virga from a thin super cooled liquid cloud base at altitudes of 2.3–9.4 km using ground-based lidars at Wuhan, China. Polarization lidar profile (3.75 m) analysis reveals the vertical structures and phase states of both falling mixed-phase virga and their liquid parent cloud layers. Based on one year of polarization lidar measurements at Wuhan, China, Wang *et al.*[2] studied geometrical and optical characteristics of cirrus clouds. They found that there is a positive correlation between the cirrus occurrence frequency and dust column mass density in seasons except summer. It was revealed that the formation processes of cirrus clouds are significantly impacted by the dust particles.

It has been widely confirmed that a close coupling exists between the lower and upper atmosphere. The activities at the lower atmosphere may produce a chain reaction in the middle-upper atmosphere. Based on the joint observations by an atmospheric electric mill, a fluxgate magnetometer, a temperature/wind lidar, an ionosonde, and the World Wide Lightning Location Network, Qiu *et al.*[3] revealed a conjunction between the lower and upper atmosphere. The key interconnected processes could be suggested to be: lightning strokes → overturning of the electric field → ionospheric sporadic E (Es) generating a sodium layer (Nas).

The need of scientific research promotes the development of lidar techniques. Yanqing (40°N, 116°E) is one of the most important lidar stations in the lidar chain of CMP. In the past two years, this lidar station has scored big points rapidly. A new Ni lidar has been designed and deployed there, which can effectively avoid the disturbances by Amplified Spontaneous Emission, and detect the Ni layer successfully. The nightly-averaged Ni densities observed by Yanqing lidar are similar to the results reported by Gerding *et al.*[4]. Taking advantage of high-resolution detecting mode of Yanqing Na radar, Zou *et al.*[5] successfully accomplished observations of the spectrum of a gravity wave in the turbulence region.

2.1.2 Dynamics and Planetary Waves in the Middle and Upper Atmosphere

Severe weather events in the lower atmosphere, such as thunderstorms, cyclones, tropical storms, typhoons *etc.*, produce waves by disturbing local atmosphere. These waves can propagate upward to the Mesosphere and Lower Thermosphere (MLT) region under appropriate conditions, exciting disturbances at these latitudes. It is an important coupling process between the lower atmosphere and the MLT region. The waves from the lower atmosphere bring energy and momentum to the MLT region, and then affect the dynamic structure of the whole atmosphere. The first phase of CMP has deployed multiple radio and optical instruments. It provides valuable first-hand experimental data for the in-depth study of dynamic processes and waves in the middle and upper atmosphere over China.

Based on the long-time observations of Wuhan MST radar and Beijing MST radar of CMP, Zhang *et al.*[6] studied the statistical characteristics of the mesospheric vertical wind at mid-latitudes for the first time and described the diurnal, seasonal and annual variation characteristics of the vertical wind at Wuhan and Beijing. No prominent subdaily and seasonal variations are found. It was shown that there are differences between the summer vertical winds over Beijing and Wuhan. The differences are mainly related to the gravity wave activities.

Sudden Stratospheric Warming (SSWs) occur in the stratosphere of polar regions in the winter. It has a significant and severe impact on the atmosphere in all regions and latitudes (from the ground to hundreds of kilometers) of the world. Thanks to the observations with the meteor radar chain of CMP, some scientists have studied the variation characteristics of planetary waves and tidal waves in the middle and upper atmosphere during SSW events. Li *et al.*[7] systematically analyzed the disturbance characteristics of atmospheric wind field and tidal waves in the MLT region during an

SSW event in 2013. It was found that during this event, there was a sudden increase of northward wind in the latitudes of 18°N–53°N in China, and the diurnal tide and semidiurnal tide weakened first and then increased. There are obvious latitudinal differences in the response characteristics of MLT atmospheric wind field and atmospheric tide to the SSW event in 2013. Gong *et al*.[8] presented that the Quarter Diurnal Tide (QDT) abnormally enhanced during the 2019 Arctic SSW event. Luo *et al*.[9] found that the quasi-10-day Waves (Q10 DWs) were enhanced during an SSW event in February 2018 as well. Ma *et al*.[10] analyzed planetary-scale oscillations in the MLT region during SSW events. They revealed that the enhancement or generation of westward propagating quasi-16-day oscillation with wave number 1 is a common feature during SSWs over Mohe. They also analyzed a strong enhancement of the quasi-4-day oscillation during the 2018/2019 SSW, and presented the interpretation of formation mechanism. Their results not only showed that the amplified quasi-4-day oscillation in the MLT region is associated with the 2018/2019 SSW but also suggested that the amplification is originally generated around 60 km due to the instability caused by the drastic changes of local temperature and wind field and propagates upward to MLT region.

The atmospheric waves can also propagate upward, which are one of the main sources of ionospheric changes. Huang *et al*.[11] found that there was a significant daytime TEC enhancement several days before the occurrence of SSW in 2017, with a range of 75%–160%; This event is a typical case of coupling between different atmospheric spheres and provides important evidence of lower atmosphere-ionosphere coupling. Liu *et al*.[12], for the first time, described the response processes of the ionospheric parameters from the middle atmosphere to the top of ionosphere during SSW. From the point of view of the disturbance period, the quasi-16-day planetary wave scale disturbance in the ionosphere during SSW is related to semi diurnal and lunar tides. Mo *et al*.[13] studied the multiscale planetary wave scale disturbance of the ionospheric Equatorial Anomaly Peak (EIA). It is found that the periodic disturbance of planetary waves in ionospheric EIA is obviously modulated by the semidiurnal tide in the lower atmosphere, indicating the role of tidal modulation in the planetary wave scale coupling process between the lower atmosphere and ionosphere.

The measurement of winds is one of the key data to study the dynamic process of the middle and upper atmosphere. At present, the detection of winds mainly depends on ground-based equipment and satellites. Jiang *et al*.[14] compared the GOCE crosswind data with the horizontal winds measured by ground-based FPIs. It was found that during magnetically quiet periods the GOCE observations are in a good agreement with FPIs measurements in the magnitude and seasonal variations of winds. However, the GOCE and FPI derived winds have a lower agreement during geomagnetically active periods, which deserves further study. We all know that ground based observation has the advantage of continuous time coverage and satellite observation has the advantage of space coverage. Taking advantage of these two means comprehensively, Liu *et al*.[15] obtained the global wind field information with a large vertical span from the stratosphere to the lower thermosphere and a large time span of 18 years, which meets the urgent demand for wind field data in the research and application of middle and upper atmospheric dynamics to a certain extent.

2.2 Study on Ionosphere

2.2.1 Variation Characteristics of Ionosphere

The Earth's ionosphere exhibits complex variation characteristics. One standard feature of the ionospheric variations is the diurnal variation, which is the fundamental of ionospheric empirical models. Liu et al.[16] used the Qujing incoherent scatter radar in conjunction with ionosondes to investigate the feature of the enhancements of electron density in the ionospheric F region at low altitudes. The characteristic of decreasing h_mF_2 and increasing N_mF_2 may present at both nighttime and daytime. That is to say, the compression of the ionosphere certainly causes an increase in the low-latitude electron density and a lower peak height.

Another important feature is the day-to-day variability of the ionospheric electron density and its longitudinal gradient. Liu *et al*.[17] reported a typical case of anomalous enhancement in ionospheric electron density and its longitudinal gradient during the period from 29 May to 2 June 2015. It is shown that electron density enhances strongly in the region around the northern crest of equatorial ionization anomaly; the increase in electron density depends on altitude, being stronger at higher altitudes; the electron density enhancement event is well correlated with an intensified equatorial electrojet.

The ionosphere presents complex changes under the control of dynamic processes. Sometimes the ionospheric electron density increases with local time under the action of dynamic processes. That is the nighttime enhancement. Li *et al*.[18] statistically explored the feature and mechanism of the ionospheic nighttime enhancement at midlatitudes. The results showed that the dynamic process controlling the nighttime enhancement at midlatitudes in winter is obviously different from that in summer. In winter, the change of h_mF_2 has no significant effect on the characteristics of nighttime enhancement. Downward plasma influxes from the topside ionosphere and the conjugate summer hemisphere play a decisive role in the formation of nighttime enhancement.

2.2.2 Ionospheric Irregularities

Ionospheric irregularities refer to various scale ionized "clouds" or "wavy" structures floating in the normal ionospheric structure. The study of ionospheric irregularities not only helps to further understand the physical process of ionospheric disturbance and change, but also has important engineering and application value.

The special daytime E Region V-shaped echo pattern in Range-Time-Intensity (RTI) plots of VHF radar was investigated by two groups independently. Chen *et al*.[19] presented the common features of V-shaped echoes by four cases studies. The V-shaped echoes usually occur between 10:00–15:00 LT in the daytime with the enhanced top frequency and blanketing frequency of Es layer ($f_{t,Es}$ and $f_{b,Es}$). Their left/right wings present negative/positive Doppler velocity. In another case study, Sun *et al*.[20] connected the V-shaped radar echoes with the strong Es. The band-like strong Es structures with critical frequencies up to about 17 MHz were analyzed within the ionosonde and VHF radar fields-of-view, which caused unique V-shape backscatter radar echoes with negative (positive) Doppler velocity and range rate in the left (right) wing of the echo that was ascribed to the drift of the strong Es structure and wide beams of the radar sets.

Ionospheric F region bottom-type irregularity layer was first reported by Fuke and Sanya VHF radar observations in 2017. Hu *et al*.[21] extended the bottom-type irregularity study with an eight-year observation by Sanya VHF radar during the equinoctial months of 2011–2018. The results showed the bottom-type irregularity layer occurred almost exclusively in the descending phase of the solar cycle (2015–2018). No clear correlation was found between the occurrences of bottom-type irregularity layer and plasma plume at low latitude.

Equatorial Plasma Bubble (EPB) and Medium-scale Traveling Ionospheric Disturbances (MSTIDs) are important ionospheric irregularities. The occurrences of EPB irregularities over Asian and American sectors often show different behaviors due to significantly different geometry of the geomagnetic field. Zhao *et al*.[22] presented a comparative study of long-term occurrences of EPB kilometer-scale irregularities over the two longitude sectors. The two sectors showed significant differences in seasonal variability, solar activity dependency, latitudinal variation, and magnetic activity dependency of kilometer-scale irregularity occurrence rates. The findings will help in the design of experiments to better understand how EPB irregularities are generated in the future international meridian circle project.

Xie *et al*.[23] reported that E region Quasi-Periodic (QP) echoes and F region MSTIDs were simultaneously observed at low latitudes. It was found that the QP echoes were clustered into groups coinciding with the periods of MSTIDs. They suggested that the E-F electrodynamic coupling could modulate the E region plasma instability, producing QP echoes at low latitudes. Hu *et al*.[24] investigated the occurrence characteristics of periodic TEC perturbation associated with MSTIDs. The results showed that the latitudinal variations of periodic ionospheric disturbances show two occurrence peaks at higher and lower latitudes, with a minimum identified at latitudes centered around 30°N–33°N. It was surmised that the background electron density and perturbation source could play important roles in causing the latitudinal variation of MSTIDs along 110°E. Sun *et al*.[25] investigated the effects of a post-evening Weddell Sea Anomaly (WSA)-like plasma patch on a southwestward propagating MSTID. They found some of WSA-like plasma patches moved northward from the EIA regions to midlatitudes, as they traveled westward into China. Over 50% of these structures were accompanied by concurrent MSTID and Es. They proposed that an intense Polarization Electric Field (PEF) associated with an MSTID/Es from the more northern regions of EIA could frequently drive these plasma patches poleward.

To better understand the evolution of EPB and MSTID, and the interaction between them, a ground-based airglow imager network across China that consists of 15 stations has been established (Xu *et al.*[26]). Xinglong and Fuke of these stations are supported by the CMP. Based on the data from the airglow network, Wu *et al.*[27] found oppositely MSTID in low latitudes during geomagnetically quiet night. Some MSTID structures of them propagated southwestward and others propagated northeastward. These MSTID structures encountered and interacted with each other. The interactive process of these MSTIDs should be related to their polarization electric fields. Wu *et al.*[28] used observational data from two all-sky imagers, GPS, Swarm satellite, and a digisonde to study a special EPB event. They found that these EPBs occurred in the region of plasma depletion structure. These EPBs showed different zonal drifts within a narrow longitudinal zone which should be related to the zonal winds. Sun *et al.*[29] investigated an interaction between an EMSTID and an EPB in the EIA crest region over China. Interaction could have polarized one depletion of the post-midnight EPB, inside which freshly-generated meter-scale irregularities caused activated radar echoes and enhanced Ranged Spread F (RSF) over Fuke station. The result showed how an electrical couple of EMSTID and EPB events can activate a post-midnight EPB depletion over low latitudes of China. Luo *et al.*[30] reported a special MSTID event observed by multi-instruments over mid-latitude region of China. They found the inclination angles of MSTID bands were decreasing, resulting in the propagation direction changed from southwestward to nearly westward. The result showed the MSTIDs disappeared partly in the airglow observation when they propagated to lower latitudes (below 40°N) later. Based on the observations from the FPI and the simulations from the TIEGCM, they found that the variations of propagation direction and the disappearance of MSTIDs should be related to the variations of ionospheric neutral winds.

2.2.3 Characteristics of Sporadic E (Es)

The Es layer is a thin and dense layer composed of metallic ions in the altitude of 90–130 km of Earth's upper atmosphere. It was observed in the 1960s that there is seasonal variation in the Es layer. However, the mechanism driving the seasonal variation is still a big puzzle for us. Yu *et al.*[31] reported that Es layer has an obvious meridional transportation from winter hemisphere to summer hemisphere. This trans-hemispherical transportation of metallic ions within Es layer is mainly controlled by the lower thermospheric meridional circulation. Apart from the seasonal variation, Yu *et al.*[32] presented that the change of metallic ions within Es layer has a strong 27-day period, meaning that the Es layer is influenced by high-speed solar winds generated from persistent coronal holes on successive 27-day solar rotations and geomagnetic activities.

Based on the observations from GNSS TEC, Sun *et al.*[33] investigated the morphology and dynamics of large-scale strong Es structures in the East/Southeast Asian sector. It was found that the large-scale strong Es structures mainly occur during summer months, with dominant horizontal azimuth in the east-west and northwest-southeast directions and dimensions of 1000–3000 km along the elongation. They predominantly drift southwestward at a speed of 30–210 $m\cdot s^{-1}$. The main onset region for the large-scale Es structures over China is identified for the first time, which is around 20°N–45°N and 100°E–125°E. Furthermore, they proposed a High Temporal Resolution Rate-Of-TEC Index (HR-ROTI) based on the 1 s resolution TEC to characterize fine scale Es irregularity structures. It was found the typical scale size of Es embedded in the strong Es structures was down to about 7 km[34].

Based on the observations from a longitudinal chain and a latitudinal chain of ionosondes including three ionosondes in CMP, Tang *et al.*[35] investigated the Es occurrence rate and variation. It was found that the occurrence rate of Es at the American sector is lower than that at European and Asian sectors; the seasonal variations of Es occurrence and strength are related to the annual variation of meteor counts; aside from the impact of planetary waves in the MLT region, solar and geomagnetic activities can contribute to the periodic oscillations in the Es layer variations as well. Tang *et al.*[36] used observations of ionosodes and meteor radars to study the mechanism of middle- and low-latitude Es layer formation. It is shown that Es layer can form at low-latitude non-wind shear points as well, and its formation can be affected by the turbo-pause at 90–105 km.

2.3 Observations and Researches on Polar Region Ionosphere

The Earth's polar region is its natural window to the space. The magnetic field lines are highly aggregated and nearly open to space vertically. Therefore, the high-energy particles from solar wind can directly "hit" the atmosphere over the Earth's north and south poles, where auroras light up. Various dynamic processes caused by the interaction between the solar wind and the Earth's magnetosphere can be directly mapped to the polar ionosphere, which makes the processes of plasma precipitation and transportation in the polar ionosphere complex, and is accompanied by many irregular structures there. Polar cap patch is the most common irregularity in the polar ionosphere.

2.3.1 Space Hurricane

Zhang *et al*.[37] discovered a hurricane-like phenomena above the ionosphere around the Earth's magnetic north pole under low solar and otherwise low geomagnetic activity, and named it "space hurricane". They found the space hurricane has similar characteristics to the typhoon or hurricane in the lower atmosphere: a coincident cyclone-shaped aurora, strong circular horizontal plasma flow with shears, a nearly zero-flow center, enhanced electron temperature, ion upflows, a circular magnetic field perturbation, and strong electron precipitations, *etc.* The observations and simulations revealed that the space hurricane is generated by steady high-latitude lobe magnetic reconnection and current continuity under extremely quiet conditions.

2.3.2 Observations of the Polar Ionosphere and Aurora

The monitoring instruments deployed by the CMP in the polar region provide effective means for the study of the polar ionosphere. Based on the satellite observations and the ground observations from Zhongshan Station in Antarctica, along with the 3D MHD simulation, Zhang *et al.*[38] reported that unusually bright and multiple Transpolar Auroral Arcs (TPAs) appear in the polar cap region of Antarctica when the Interplanetary Magnetic Field (IMF) is northward and geomagnetic activity is quiet. These multiple TPAs are generated by precipitating energetic mangetospheric electrons within Field-Aligned Current (FAC) sheets. These FAC sheets are generated by multiple-flow shear sheets in both the magnetospheric boundary and the plasma sheet. Their study offers a new insight into the complex solar wind-magnetosphere-ionosphere coupling processes under a northward IMF.

There are many kinds of irregularities in the polar ionosphere. It is particularly important to investigate the formation mechanism and evolution characteristics of these large-scale irregularities. Wang *et al*.[39] developed a new method named Total Electron Content (TEC) keogram based on a movie of TEC maps. A clear train of polar cap patches was identified from the TEC keogram and confirmed by SuperDARN radar observations. This tool offers a powerful tool for monitoring and studying large-scale plasma irregularities in the polar ionosphere. The structure and evolution of polar ionospheric irregularities show closely dependence on solar and geomagnetic activity. Zhang *et al*.[40] presented a statistical survey of polar cap patches in relation to solar and geomagnetic activity. They found that the occurrence of cold patches is obviously dependent on solar and geomagnetic activity, while hot patches do not show such dependence. It was also found that the spatial size of both cold and hot patches decreases (increases) with solar (geomagnetic) activity. The poleward expansion of the active aurora region following substorm auroral onset is often associated with a bulge region that expands westward and forms the westward travelling surge. Ma *et al*.[41] observed two surge events to study the relationship between the surge and ionospheric flows that likely have polar cap origin. They first demonstrated that the flow of polar cap origin, which maps to underlying processes in the magnetotail, may play a crucial role in the formation and development of the westward travelling surge.

2.4 Responses of Geospace to Solar Activities

2.4.1 Influence of Solar Radiation Variation on Magnetosphere

The solar wind plays an important role on the Earth's magnetosphere, but it is unclear whether the same holds for solar flares. Liu *et al*.[42] and Liu *et al*.[43] have studied the effects of flares on the Earth's magnetospheric dynamics and the magnetosphere-ionosphere electrodynamic coupling. Their studies showed that the ionospheric conductance sharply increases with the enhanced solar radiation. The increased ionospheric conductance reduces the efficiency of mechanical energy conversion in the dayside solar wind-magnetosphere interaction, resulting in less Joule heating of the Earth's upper atmosphere, a reconfiguration of magnetosphere convection, as well as changes in dayside and nightside auroral precipitation. Their works demonstrate that solar flare effects extend throughout the geospace via electrodynamic coupling.

2.4.2 Influence of Solar and Geomagnetic Activities on Ionosphere

The mid and low latitude ionosphere shows complex responses to the geomagnetic storm and solar flare. Using multiple measurements of Beidou Geostationary Orbit (GEO) satellite and MIT Madrigal Total Electron Contents (TECs), ionosondes, magnetometers, and Global Ultraviolet Imager, Li *et al*.[44] reported that the daytime ionosphere displayed strong positive rather than negative storms at multiple longitude sectors in the mid- and low-latitudes during the recovery phase of August 2018 geomagnetic storm. They revealed that the enhanced upward vertical plasma drifts make an important contribution to the positive storm, while the drifts could not be driven by the common storm-induced source. Using aurora, high-latitude convection, potential data sets from DMSP satellite and SuperDARN radar combined with model simulation, Ren *et al*.[45] further disclosed that high-speed solar wind stream was a possible but not the main driver to the mid- and low-latitude ionospheric positive storm during the August 2018 geomagnetic storm recovery phase. Using Beidou GEO TECs at 4 stations of the 120°E longitudinal chain of CMP, Jimoh *et al*.[46] statistically disclosed the occurrence characteristics of the daytime TEC enhancements during geomagnetic storm and quiet geomagnetic conditions. The TEC enhancements displayed a preference for the September equinox and December solstice at the middle and low latitudes, respectively. Moreover, the occurrence during the main phase of geomagnetic storms was significantly above the TEC enhancement baselines, while it exhibited recurrence of TEC enhancements during the recovery phases. Owolabi *et al*.[47] compared the global ionospheric currents in response to X9.33 disk and X8.28 limb solar flares, using the ground-based magnetometer data. They showed that the ionospheric currents displayed an asymmetrical pattern though the flares happened in equinox. The total current intensity changes are stronger in X8.28 than in X9.33 flare, although X9.33 flare has much more solar flux. The enhanced ionospheric conductance along with the associated electric field changes result in the observed ionospheric current variations during the flares. The longitudinal variations of the magnetic field and the seasonal effect could also play an important role.

2.4.3 Ionospheric Changes Caused by Solar Eclipse

Sudden changes in solar radiation caused by instantaneous solar activities such as solar eclipses and solar flares will significantly affect the solar radiation reaching the Earth. The change of solar radiation is the most important driving force of ionospheric change. Chinese scientists studied the responses of ionosphere to the annular eclipse on 21 June 2020. Zhang *et al*.[48] investigated the ionospheric responses to the 21 June 2020 annular solar eclipse using the ionosondes and GNNS-TEC data from the CMP. The results revealed that the ionospheric responses to the eclipse are not only restricted in the Moon's shadow, but also in the conjugated hemisphere, which is suggested to be due to the coupling effect from the electric field, neutral wind, thermal conduction, and interhemispheric photoelectron transport. In addition, Huang *et al*.[49] further investigated the low-latitude ionospheric responses to the annular solar eclipse using the Beidou GEO TEC and ionosondes data from the CMP and in-situ N_e and T_e in SWARM and CSES satellites. They found that the TEC evidently decreases with the obscuration and undergoes a considerable decrease in the EIA region in the conjugate hemisphere. The TEC and N_e at low latitudes showed a long-lasting response for over 7 h. after the eclipse. The relevant TEC and N_e changes could be attributed to the obscuration rate and the eclipse induced perturbations of dynamic processes.

2.4.4 Effects of Geomagnetic Storms on Ground-based Instruments

During geomagnetic storms, the drastic change of geomagnetic field induces an electric field on the ground, driving currents in long-distance conductive ground-based systems, such as power grids, pipelines, and railway systems. The currents are named as Geomagnetically Induced Currents (GICs). Large GICs can pose a threat to those ground-based instruments. The study of GICs events has become the research hotspot in space weather over recent years. The geomagnetic and geoelectric field data of the CMP provide powerful support to the GICs research including its measurement, modeling, forecasting, and hazards assessment, *etc*.

Zhang *et al*.[50] studied the GICs characteristics at a Chinese low-latitude substation during geomagnetic storms. They then built a physical-based model to simulate the GICs at the low-latitude substation during storms. The model can capture the main active periods and strength of the GICs during the storms compared with the measurement. Its performance is better than the persistence model.

2.5 Progress on the Method of Detection and Data Processing

In recent years, a number of ground-based space environment monitoring systems have been completed or put into construction (such as the second phase of CMP), which provide monitoring data support for the research of key scientific problems of space physics and the prediction of key parameters of space weather over China. In the last two years, with the rapid development of detection facilities, detection methods and data processing methods have also made remarkable progress. Based on the Ensemble Kalman filter data assimilation system, He *et al*.[51] evaluated the effect of different radio observation systems on the nowcasting and forecasting of key ionospheric parameters (such as TEC and three-dimensional electron density) over China and the adjacent region. Xu *et al*.[52] proposed a method for retrieving the Perceptible Water Vapor (PWV) along the line of sight toward the science target using the OH (8–3) band airglow spectrum. To verify the method of PWV retrieval, they made cross comparisons between the PWV retrieved from OH airglow and PWV from the standard star spectra of Ultraviolet and Visual Echelle Spectrograph (UVES). Kong *et al*.[53] proposed a post-processing scheme to infer the electronic characteristic energy of the aurora based on the spectral data of ground-based auroral spectroscopic imager located in Antarctica Zhongshan station. In order to improve the inference rate, classical brute-force, recursive brute-force and self-consistent approximation strategies have been adopted successively. The inferred characteristic energies are compared to the average energies calibrated from the relevant electron data detected by the particle detectors SSJ5 on the DMSP satellite to prove the effectiveness of the inference model. These two energy estimations about auroral electrons show a strong linear relationship. It sheds light on further applications of the valuable aurora spectral data.

3 Summary and Prospect

In this report, we review the highlight studies done by scientists in the past two years using the monitoring data of the first phase of CMP. As the first and only national major scientific and technological infrastructure in the field of space environment monitoring in China, the CMP has already operated stably and efficiently for ten years, produced a series of high-quality monitoring data, met the major strategic needs of space weather forecasting for major space activities in China, and also provided strong support for the frontier scientific research of space physics. In 2019, the Chinese government supported the construction of the second phase of CMP. The second phase is expected to be completed by the end of 2023 and put into formal operation. At that time, the first phase of the project will be fully integrated into the second phase. The CMP will operate as a whole, and continue to contribute to China's cutting-edge scientific and technological innovation in the field of space science and even interdisciplinary disciplines.

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