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Scientific challenges and instrumentation for the International Meridian Circle Program

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Abstract Earth's ecosystems and human activities are threatened by a broad spectrum of hazards of major importance for the safety of ground infrastructures, space systems and space flight: solar activity, earthquakes, atmospheric and climatic disturbances, changes in the geomagnetic field, fluctuations of the global electric circuit. Monitoring and understanding these major hazards to better predict and mitigate their effects is one of the greatest scientific and operational challenges of the 21st century. Though diverse, these hazards share one feature in common: they all leave their characteristic imprints on a critical layer of the Earth's environment: its ionosphere, middle and upper atmosphere (IMUA). The objective of the International Meridian Circle Program (IMCP), a major international program led by the Chines Academy of Sciences (CAS), is to deploy, integrate and operate a global network of research and monitoring instruments to use the IMUA as a screen on which to detect these imprints. In this article, we first show that the geometry required for the IMCP global observation system leads to a deployment of instruments in priority along the 120°E–60°W great meridian circle, which will cover in an optimal way both the dominant geographic and geomagnetic latitude variations, possibly complemented by a second Great Circle along the 30°E–150°W meridians to capture longitude variations. Then, starting from the Chinese Meridian Project (CMP) network and using it as a template, we give a preliminary and promising description of the instruments to be integrated and deployed along the 120°E–60° W great circle running across China, Australia and the Americas.

Keywords International Meridian Circle Program, Ionosphere, Middle-upper atmosphere, Space weather, Chinese Meridian Project

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1. Introduction

Our terrestrial environment is coupled to the Earth's magnetosphere and its boundaries with the Solar Wind and interplanetary space via a critical layer: its Ionosphere, Upper and Middle Atmosphere (IMUA). Within this critical layer, the neutral and plasma components of our atmosphere and the geomagnetic field are strongly coupled via complex electrodynamic interactions. As a result of these interactions, the IMUA is permanently influenced by its coupling with the regions of space located above and below it, and by coupling processes within the IMUA, as shown in Figure 1: from

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above, solar activity and interplanetary space disturbances produce the so-called space weather events, which perturb the Earth's magnetosphere and the IMUA to which it is coupled; disturbances propagating from below, mediated by atmospheric waves, electrodynamic coupling and electromagnetic radiation, are generated by earthquakes, the variability of solar irradiance, weather systems, and emissions of greenhouse gases; finally, secular changes of the geomagnetic field, which take place over time scales of years to centuries, and transient variations in the global atmospheric electric circuit connecting thunderstorms to the conducting layers of the ionosphere, perturb the global electric current systems coupling the lower atmosphere, ionosphere and magnetosphere, and modulate all energy transfer processes throughout geospace.

Understanding how the IMUA is affected by this diversity of disturbances in order to untangle their different effects and read the message they convey about the different types of threats to our living environment, is a major scientific and societal issue for the 21st century. Since the IMUA is affected by all types of natural and anthropogenic hazards, we can use it as a screen on which to better recognize, understand, mitigate and sometimes predict the broad spectrum of natural and human-made threats on our ecosystems and human activities: solar activity, earthquakes, atmospheric and climatic disturbances, changes in the geomagnetic field, fluctuations of the global electric circuit. We will also be able to better quantify their effects on the Earth's space environment and on the safety of space and ground infrastructures.

Meeting this ambitious goal requires the coordinated scientific operation of a global network of ground-based instruments to continuously measure the key parameters of our ionosphere, middle and upper atmosphere. This is the overarching goal of the International Meridian Circle Program (IMCP), an ambitious international scientific program led by CAS, which can be formulated as follows:

Monitor the major perturbations on our human environment by means of the operation of a global network of instruments observing continuously the Ionosphere and Middle-Upper Atmosphere (IMUA), and use the systematic observations it produces to understand, mitigate and in some cases forecast these perturbations.

An international forum jointly organized in Beijing in September 2019 by the IMCP office and the International Space Science Institute (ISSI)-Beijing on the premises of the National Space Science Centre, CAS, defined the science questions to be addressed by the IMCP, produced a preliminary design of its observation system, and formulated the principles of its data analysis and modelling component, see the forum report (Liu et al., 2020a). This "News Focus" article is a summary of its conclusions and recommendations, and complements the contribution of the IMCP program to the Chinese National Report to COSPAR (Liu et al., 2020b) in three specific areas: the Science Case for the IMCP, the design of a global observation system driven by this Science Case, and the modelling and data assimilation approach of the IMCP.

2. The IMCP science case

The environment of Earth is impacted by changes in three of its principal drivers: variations of solar activity between successive solar cycles (Delaigue, 2019), the current fast decrease of the terrestrial magnetic field dipole intensity and drift of its poles (Mandea and Purucker, 2018) and, finally, fast anthropogenic increase of greenhouse gas emissions (Stocker et al., 2013). Understanding the interplay of these changes requires a world-wide network of instruments to observe the different types of perturbations illustrated in Figure 1, whose corresponding time scales are indicated below in brackets:

A. Disturbances induced by Solar Activity and interplanetary space on the magnetosphere and ionosphere (minutes to decades and more);

B. Weather disturbances in the lower atmosphere (hours to years);

C. Effects of climate change on the upper atmosphere and ionosphere (months to decades);

D. Seismic activity (seconds to years);

E. Mid-to-long term variations of the geomagnetic field (decades to centuries and more).

Each of these types of perturbations will be studied by use of the IMCP global network of instruments to address the following three questions: (1) How do their effects propagate to the IMUA? (2) How do they disturb our space environment? (3) How to use their imprints on the IMUA to characterize and possibly predict these hazards?

By integration of the diverse requirements for the spatial coverage of the sources and/or effects of hazards A to E, one can determine the "ideal" geometry for the IMCP observation system. In order to do this, let us inspect the Mercator maps of the sources and effects of these disturbances shown in Figure 2: contours of equal geographic and geomagnetic latitudes, relevant for disturbances A and E (Figure 2a); maps of the average tropospheric circulation showing the zonal band and land-ocean contrasts, relevant for disturbances B and C (Figure 2b); world distribution of the occurrence of earthquakes (Figure 2d); global distribution of lightning stroke impacts (Figure 2c). The red full lines and das-dotted vertical lines on each panel show the 120°E–60°W and the 30°E–150°W Great Circle, respectively. Figure 2 inspires the following comments:

(1) Most types of disturbances mainly vary with geographic (disturbances B and C) or geomagnetic latitude

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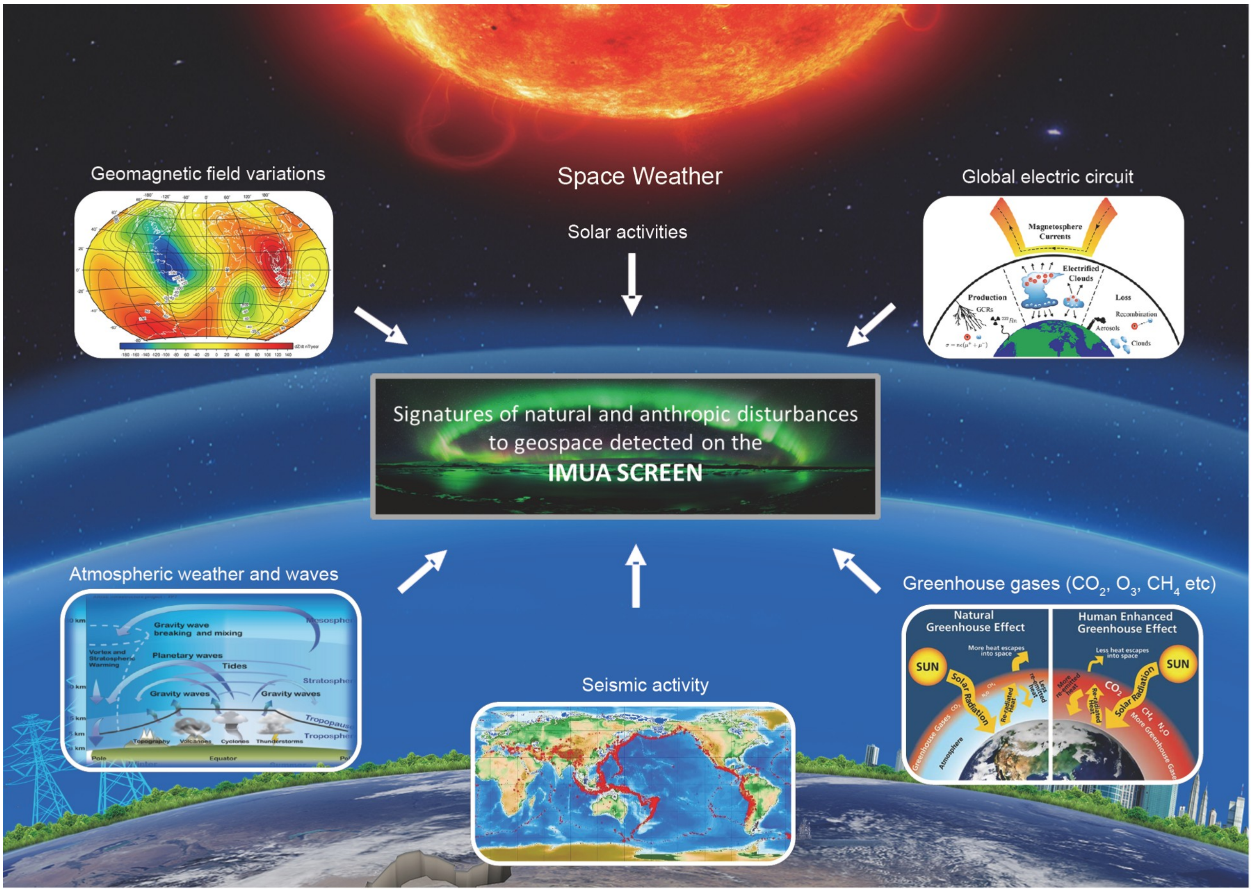

Figure 1 A summary of the different types of disturbances of the Sun-Earth system (space weather, terrestrial and solar magnetic field long-term variations, greenhouse gases emissions, global atmospheric electric circuit transients, seismic activity, atmospheric waves) that can be detected on the IMUA screen.

(disturbances A and E). This dominant latitude dependence goes along with a significant longitude dependence for disturbances B and C (tropospheric weather and climate), mainly due to the land-ocean contrast.

(2) Since the first characteristics of the IMCP instrument network must be to provide the best possible coverage of both geographic and geomagnetic latitudes, the 120°E–60°W Great Circle, extending through east Asia, west Australia and the Americas and running very close to the geographic and geomagnetic poles, is a nearly optimal choice. In addition, its broad coverage of lands facilitates the deployment of the instruments of the network.

(3) This Great Circle, which also provides a reasonable coverage of the easternmost and westernmost edges of the circum-Pacific ring of fire, is also a very good choice to monitor seismic and volcanic hazards (Disturbance D) over the most active regions of the globe.

(4) In addition to this primary circle, to capture the significant longitude variations of hazard sources induced by land-ocean contrasts and by the geographic longitude asymmetries of the geomagnetic field, a secondary Great Circle in longitude quadrature with the first one, i.e. the 30°E–150°W meridian, will be very useful. It covers central Europe and Africa and runs across the Pacific from Alaska to French Polynesia. The map of the distribution of lightning strokes (Disturbance B, Figure 2c) shows that this second Great Circle passes over the region of worldwide maximum lightning occurrence in central Africa.

(5) By combining data from the two Great Circles, the pronounced longitude variations in seismicity and thunderstorm activity will be observed.

In conclusion, analysis of the spatial distributions of all hazard sources shows that a "primary" 120°E–60°W Great Meridian Circle will capture all latitude variations of hazards and will be ideal to study the effects of earthquake activity along the circum-pacific ring of fire. A second Great Meridian Circle along the 30°E–150°W longitudes will capture the residual longitude variations produced by land-ocean contrasts, particularly in tropospheric weather and thunderstorm activity.

3. The IMCP observation system

To deploy its network of instruments along these two great circles in its final configuration, the IMCP will integrate

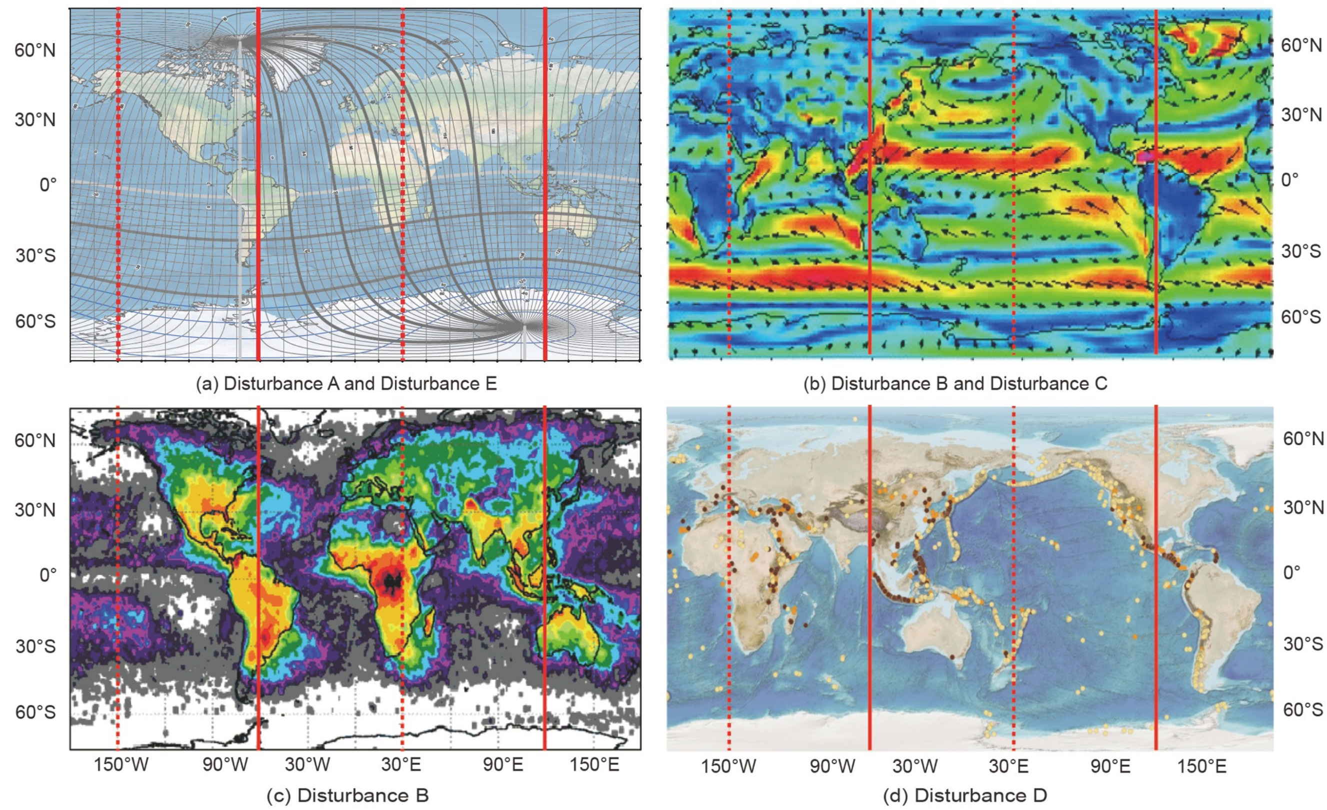

Figure 2 Summary of the unique properties of an IMCP observation system deployed along two Great Meridian Circles in quadrature, the primary 120°E–60°W meridian running over east Asia, west Australia and the Americas (full red vertical bars) and a secondary Great Circle 30°E–150°W extending over central Europe, Africa, Alaska, Hawaii, Polynesia and the Pacific (dashed vertical bars). The geographic and geomagnetic coverage offered by these two circles is near optimum for a simultaneous scientific investigation of the five categories of hazards described in this section: Disturbance A, the Sun-Earth coupling chain and space weather; Disturbance B, lower atmosphere weather, thunderstorms and the global atmospheric electric circuit; Disturbance C, climate change effects in the upper atmosphere; Disturbance D, seismic activity; Disturbance E, long-term evolution of the geomagnetic field (see Liu et al. (2020a), for a more detailed description).

existing or planned instruments operated by many countries over the world into a coherent observation system. Low-cost, standard instrument clusters and arrays will be supplemented by larger, facility-class instruments such as lidars and ionospheric radars. China's Meridian Project (Wang, 2010), whose Phase II is currently under construction, has been designed on this same principle (Figure 3). It can be used as a reference for the design of the global network of IMCP instruments, at the same time as a powerful tool for China to monitor the effects of global geospace disturbances at the regional scale.

The IMCP network of instruments will monitor the average state and disturbances thereof of the IMUA. For the Primary 120°E–60°W meridian circle, the 1000+ instruments deployed along it, once integrated into a coherent network, will provide a comprehensive cross-sectional scan of geospace from ground level to up to 3000 km altitude, including ionospheric density, temperature, electric and magnetic fields, wind fields, planetary waves, and distribution of minor species involved in Global Change. These common-format, real-time data, readily accessible through a distributed system consisting of a primary data center in Beijing and regional data centers operating on the different continents, will provide un-precedented spatial and temporal resolution along their great meridian circle field of view.

The deployment of IMCP observation instruments will follow a "string of pearls" arrangement.

(1) A small number of heavy high-resolution instruments (the "diamonds") like incoherent scatter radars (ISRs) (Resolute Bay, European Incoherent Scatter (EISCAT), the Chinese ISR in Sanya etc.) and long-range lidars will provide large-scale and intensive coverage of the key parameters of the IMUA along a few columns of atmosphere distributed on the different continents;

(2) A larger number of meso-scale facilities (the "pearls") such as Athabasca University THEMIS UCLA Magnetometer Network eXtension (AUTUMNX), Magnetometers-Ionospheric Radars-All-sky Cameras Large Experiment (MIRACLE), Transition Region Explorer (TREX)-plus will provide good-fidelity regional coverage of specific parameters in selected regions;

(3) "Diamonds" and "pearls" will be supplemented by broad-scale and global observation systems such as Super Dual Auroral Radar Network (SuperDARN), SuperMAG,

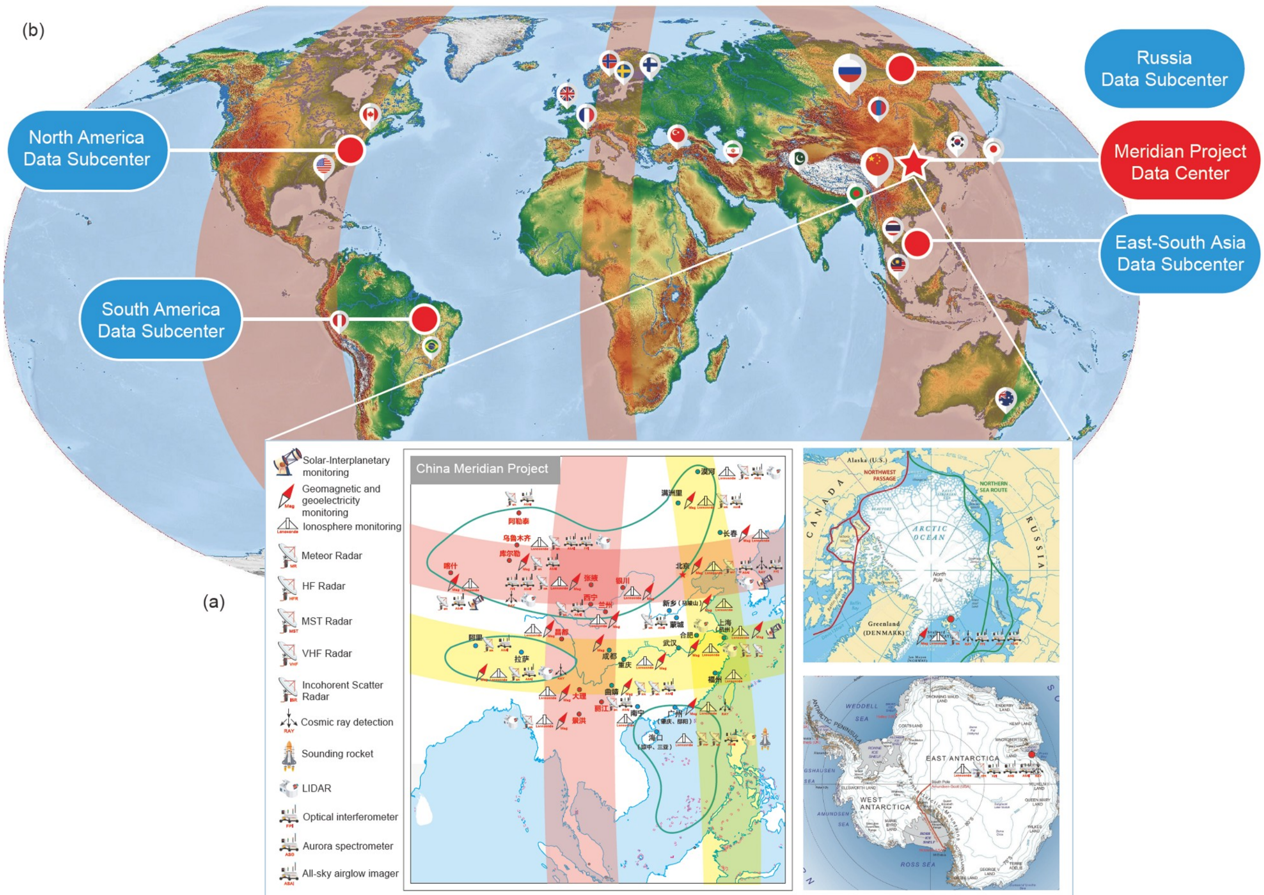

Figure 3 At the end of its implementation phase, the Chinese Meridian Project (CMP), with its combination of low-cost instrument arrays and facility-class instruments, shown in (a), will provide a dense regional-scale coverage of China and monitor disturbances occurring in the polar regions. It will be the template for the deployment of the world-wide network of IMCP instruments (b) along the two optimal great circles identified from the Science Case.

Global Navigation Satellite System (GNSS), and selected space-based observations.

(4) In between the mesoscale arrays of instruments, meridional chains of similar instrumentation provided by national efforts, preferably along the chosen IMCP meridians, can successfully supplement the coverage by the "diamonds and pearls", thus providing ample opportunities for other countries with emerging space weather organizations to join this international project in full partnership.

Given its optimal coverage of the different hazards (Figure 2), its easy deployment over several continents, and its current readiness, the deployment of the IMCP observation system along the Primary 60°E–120°W Great Meridian Circle will be the priority action of the implementation of the IMCP, constituting a Phase I of the IMCP; the deployment of the secondary meridian chain along the 30°E–150°W meridians will constitute its Phase II.

Figure 4 shows examples of instruments and networks of instruments to be deployed along the Primary Great Circle during Phase I to monitor major sources of hazards affecting our geospace and living environment: (1) a local suite of complementary instruments monitoring the atmospheric effects of seismic activity, designed to provide a "steric" coverage of the mechanisms coupling the seismogenic zone to its effects at different distances and altitudes above it; (2) a regional integrated network, the East-Siberian space weather monitoring network operated by the Russian Academy of Sciences (Siberian branch); (3) the Distributed Arrays of Scientific Instruments (DASI) project for a latitudinal chain of Fabry-Perrot interferometers (FPIs) running along the two Americas from one pole to the other, which will make it possible to study the latitudinal propagation of disturbances in upper atmosphere winds and temperatures generated by space weather events. In Appendix Table S1 (https://link.springer.com), we list some of the stations and instruments already existing and operating along the 120°E–60°W Great Meridian Circle outside China.

4. Modeling and data assimilation for the IMCP

The most advanced models, Artificial Intelligence tools and data assimilation techniques will be used to identify the

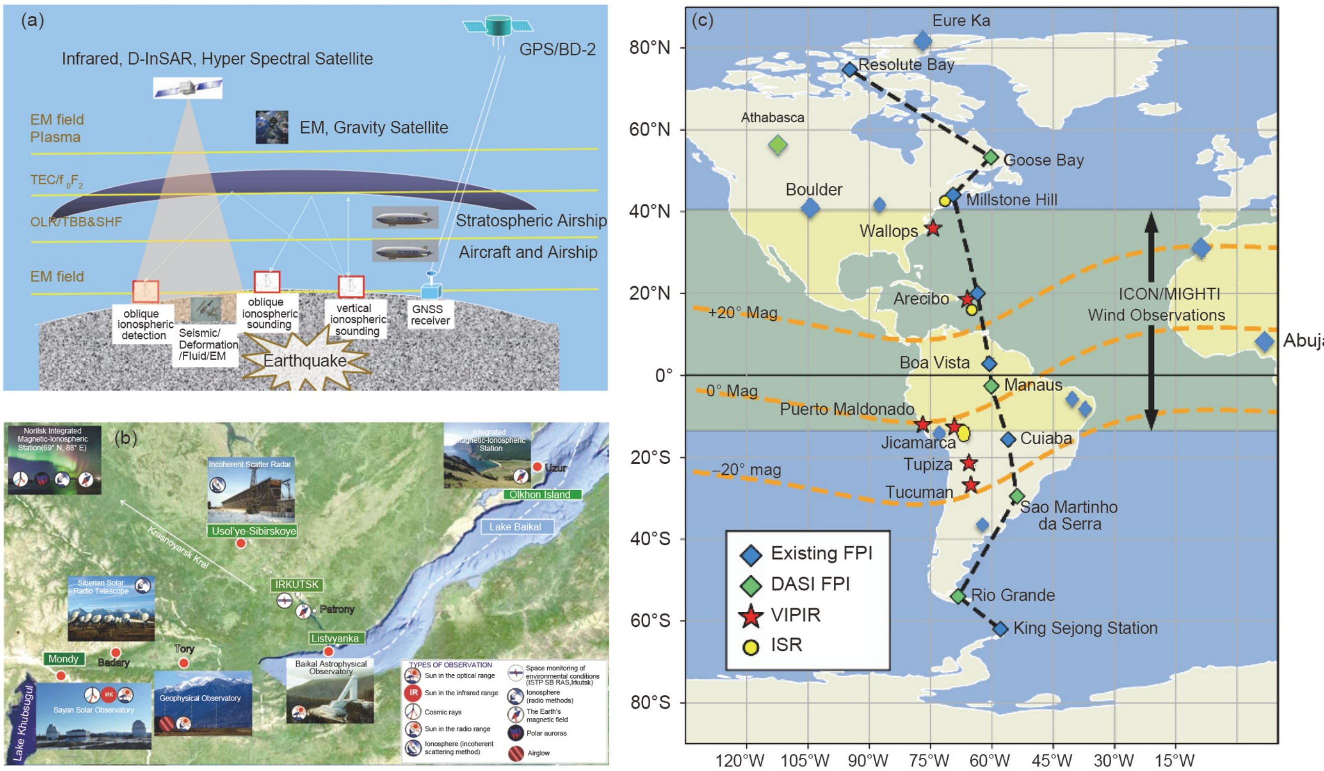

Figure 4 Three examples of the major instrument suites that will contribute to the deployment of Phase I of the IMCP observation system along the Primary 60°E–120°W Great Meridian Circle: (a) a "local" suite of instruments for the study of the atmospheric effects of earthquakes and of the coupling mechanisms between the earthquake areas and the IMUA; (b) a regional network monitoring the effects of space weather over a region: the East-Siberian network operated by the Russian Academy of Sciences; (c) the DASI project of a chain of Fabry-Perrot Interferometers running along the two Americas, which will monitor the latitudinal variations of the effects of space weather in the upper atmosphere by measuring thermospheric wind and temperature disturbances.

characteristic signatures of the different types of disturbances (A to E) on the IMUA in the very large data sets generated by the IMCP instruments. Different types of models will be used and coupled to simulate the chains of processes connecting the source regions of the disturbances to the IMUA: solar wind and interplanetary space, magnetosphere, ionosphere, upper atmosphere (for the disturbances "from above"), lithosphere, atmosphere, ionosphere (for the disturbances "from below") and global models of the atmospheric electric circuit and of secular changes of the geomagnetic field (for the disturbances "from within it").

A strong interplay between production of observational data and use of advanced numerical models will be required to achieve this objective. Advanced data assimilation techniques derived from numerical weather prediction (NWP) will be adapted to IMCP data, building on the works of Chinese researchers who have successfully applied them to ionospheric short-term prediction. A global map of total electron content (TEC) and ionospheric electron density generated through multi-sources Kalman filter data assimilation (Yue et al., 2012) is shown for illustration in Figure 5.

5. Perspectives

We have shown how the deployment and permanent operation of the IMCP observation system along the primary 120°E–60°W great meridian (phase I) will provide a continuous temporal coverage and unique latitudinal coverage of the different types of hazards affecting the Earth's geospace. The set-up of a secondary Great Circle along the 30°E-150°W meridian during phase II will subsequently improve the coverage of their longitude variations, and provide a great opportunity for European and African countries to join the project. Complementing this ground-based observation system by a specifically designed space-based component will allow one to fully separate spatial and temporal variations and to monitor critical regions of the IMUA which are not well covered by ground-based instruments, such as the lower thermosphere and upper mesosphere. The CAS-ESA SMILE (Solar Wind Magnetosphere Ionosphere Link Explorer) mission (Branduardi-Raymont et al., 2018; Wang and Branduardi-Raymont, 2018) could be the first materialization of this space segment.

More than sixty years ago, the International Geophysical Year separately studied the different layers of our planet.

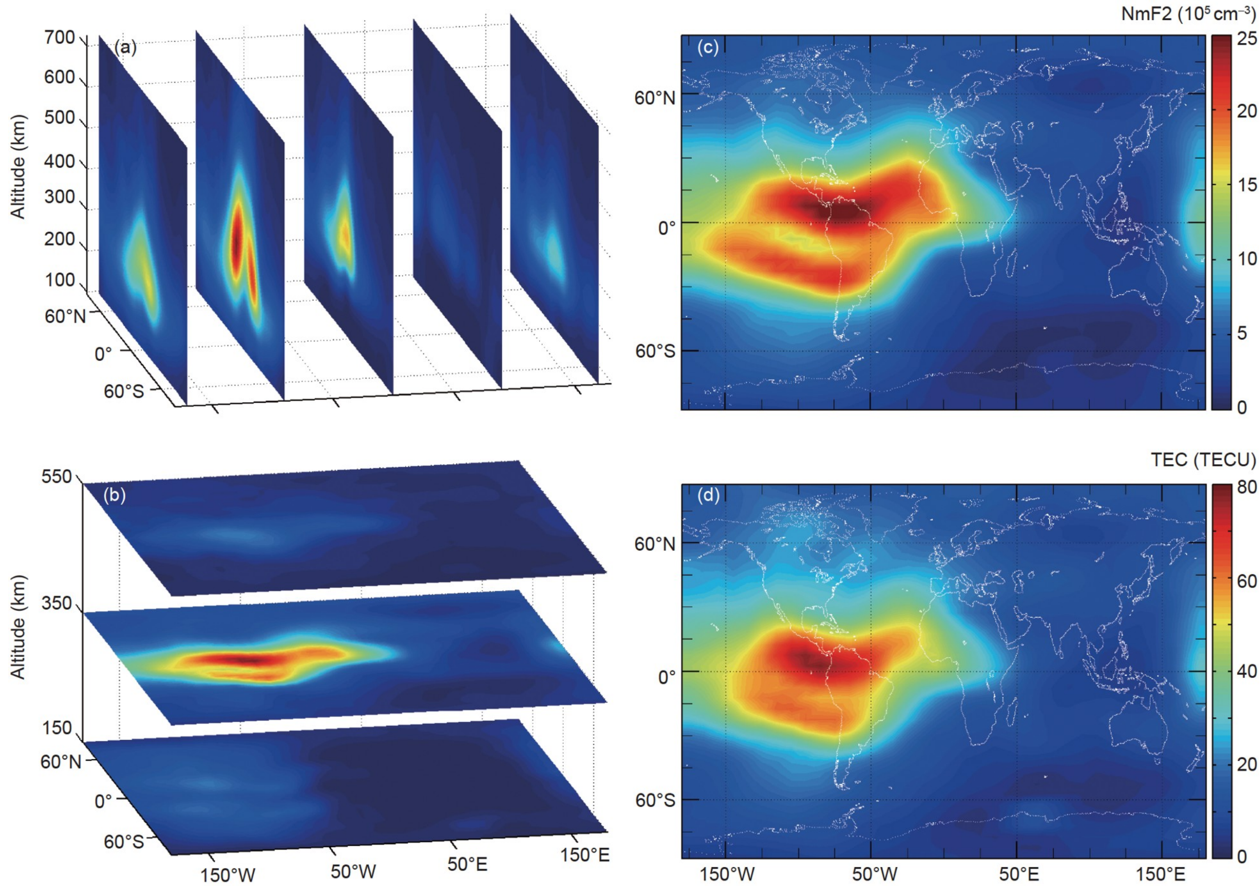

Figure 5 An example of global ionospheric electron density ((a), (b)), peak electron density (c) and Total Electron Content (d) distributions generated by data assimilation.

Addressing the most "burning" scientific questions of the 21st century requires that we encompass the Earth globally and that we understand the processes coupling its different layers. Unique among these layers, the ionosphere, middle and upper atmosphere (IMUA) behaves like a screen on which the diverse hazards threatening geospace and human activities can be detected. In particular, we pay special attention to electromagnetic couplings from the Sun all the way down to the tectonic plates and oceans. The rapid cycling time and long-range characteristics of electromagnetic interactions may be a new element in the energy processes involved in Global Change. The deployment of the global network of instruments of the IMCP would thus deepen our understanding of the impacts of space weather and natural and anthropogenic hazards on the Earth's coupled geospace and human activities.

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