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Operational Space Weather Services in National Space Science Center of Chinese Academy of Sciences

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Introduction

The National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS) was established in 1958 with the mandate to develop the first artificial satellite of China, the DFH-1. NSSC is China's gateway to space science and is the key institute responsible for planning, developing, launching, and operating China's space science satellite missions. With the development of space exploration missions in China, highly needed are the space weather forecasting services, which can greatly help to prevent or reduce the risks caused by space environment disturbances. Therefore, providing operational space weather forecasting services in enabling and enhancing national preparedness for space weather disruption has become a priority in NSSC, which is indispensable in mitigating the impacts of space weather on China's space missions and in safeguarding critical domestic infrastructure systems and technologies.

To meet the above mentioned national needs, the Space Environment Prediction Center (SEPC) in NSSC was established in 1992, which became the first professional organization and official source for providing space weather services in China [*Ye et al.*, 1997, 2000]. The formal framework of operational forecasting services was set up in 1998, since which time SEPC has been delivering continuous daily space weather predictions to the public and has been providing space weather services to customized users. SEPC/NSSC is now an associate warning center of the International Space Environment Service (ISES).

Operational Forecasting Services

The aim of the operational forecasting services at SEPC/NSSC is to monitor, specify, and forecast the space environment in order to provide timely, accurate, and reliable space weather services for domestic and international customers. The contents of services can be categorized as space weather reviews and forecasts, as well as space weather event alerts.

Space weather reviews and forecasts focus on presenting analyses of current conditions and developing trends of space weather activities, such as solar X-ray flares, geomagnetic activity, solar proton events (SPEs), and the relativistic electrons in the radiation belts. A forecaster's meeting is held every morning at 08:00 BJT (00:00 UT) to discuss the daily reviewing and forecasting product based on the latest solar-terrestrial observations and/or simulation results (Figure 1), and the final decision is updated manually at 09:00 BJT (01:00 UT). Space weather event alerts are triggered and issued automatically whenever the activity level of solar, geomagnetic, or high-energy particles reached threshold, which aim at notifying customers of space weather disruptions immediately.

The major customers of SEPC/NSSC operational services include satellite designers and operators, navigation and communication groups, geophysical research institutes, aircraft companies, radio amateurs, and pigeon associations. To understand and to meet diverse user needs are always of great importance for improving the quality of the services. Therefore, SEPC/NSSC provides both general services to the public and customized services to special users. General services include above mentioned operational forecasting products and are provided via the following approaches: SEPC/NSSC website: http://eng.sepc.ac.cn, text messages, mobile apps, and China's social networking tools: Weibo and Wechat. Customized services are tailored for special users according to their specific needs and delivering preference. Some of the typical users include China's manned space missions, Lunar Exploration, and other satellite missions such as telecommunication or navigation satellite missions.

From 1999 to 2013, there were collectively 10 Shenzhou spaceships and one experimental space station, Tiangong-1, launched into space. In order to ensure the security of all these national missions, various customized services were provided by SEPC/NSSC to reduce the risk from space weather events [*Liu et al.*, 2004;

Figure 1. Page view of SEPC/NSSC website for (top left) services delivery, (top right) mobile app "e SpaceWx", and (bottom) daily work of operational space weather forecasting services.

Shi et al., 2008; *Gong et al.*, 2010]. Commonly requested customized services are the prediction of solar and geomagnetic activity for choosing suitable launch windows, surface charging analysis for space rendezvous and dockings, radiation dose analysis of energetic particles for the safety of astronauts, thermosphere density forecasting for orbit prediction, etc. For instance, in Shenzhou-VII manned flight mission, two key experiments were carried out; one was an extravehicular activity of an astronaut, while the other one was an accompanying microsatellite experiment. The security of both experiments is at risk of extreme space weather events, such as SPEs and geomagnetic storms. Therefore, it is crucial to choose suitable launch windows and proper times for the above two experiments to avoid space weather hazards as much as possible. The customized forecasting services provided by SEPC/NSSC served as a critical reference basis for the decision-making of the mission managers.

Space Weather Monitoring Network

Adequate, accurate, and sustained space weather observations are an essential factor in establishing stable and reliable frameworks of forecasting services. Though some measurements and simulations are acquired from other international research organizations via internet, a considerable proportion of the space weather observations supporting NSSC's forecasting services comes from domestic space-based and ground-based

Figure 2. Distribution of observatories that form the Space Environment Monitoring Network (SEMnet) of CAS, along with the types of instruments deployed at each. There are three observatories in Beijing and one observatory in each other city. The central data center and operation center are at SEPC/NSSC in Beijing.

monitors. The space-based data can be collected from both meteorological satellites such as Chinese Fengyun satellites and applied satellites such as BeiDou Navigation Satellite System. For the ground-based data, NSSC has been involved in constructing two comprehensive ground-based networks in China, which have been widely used to provide wide-range, continuous, and multiparameter geospace data in supporting the operation and research of space weather forecasting services. The first network is the Space Environment Monitoring Network (SEMnet) of CAS, which is composed of 17 observatories equipped with a total of 40 instruments (Figure 2). These key instruments are responsible for providing data in near real time for the purpose of space weather monitoring and forecasting. The second network is the Meridian Space Weather Monitoring Project [*Wang*, 2010], which consists of a chain of 15 observatories located roughly along 120°E and 30°N lines, with each observatory being equipped with multiple instruments. The data derived from these instruments can be used for basic and applied research and modeling that focuses on the needs of an increasingly diverse customer community of space weather services.

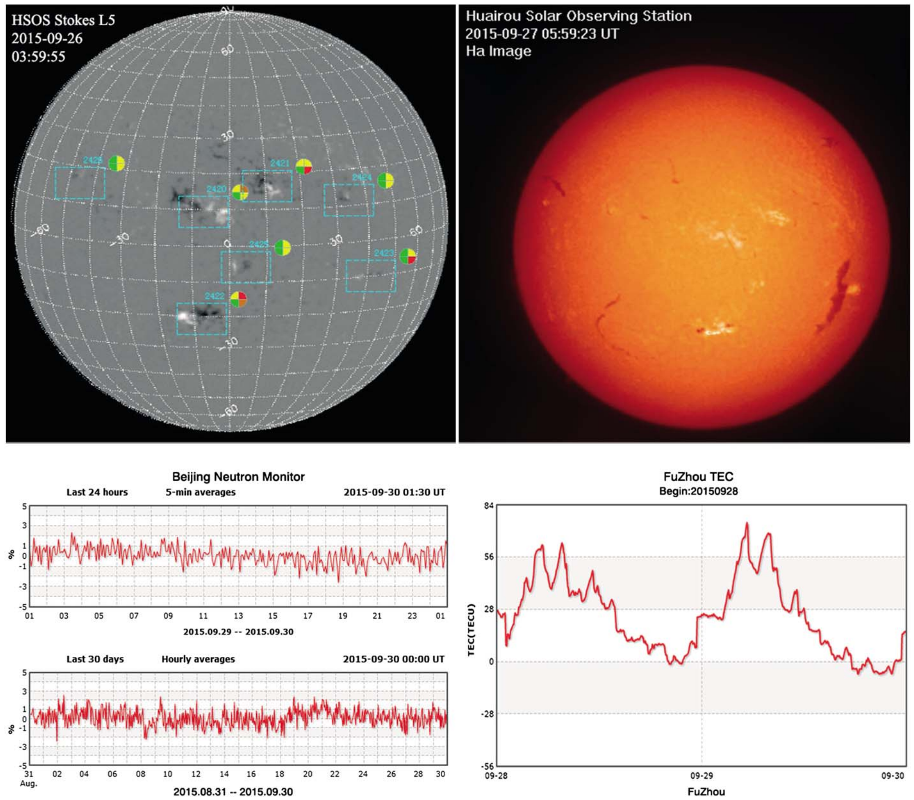

Figure 3. (top left) Magnetogram observed at Huairou solar observatory station of Beijing. (top right) Full-disk Hα image of the Sun observed at Huairou solar observatory station of Beijing. (bottom left) Cosmic ray observed at Beijing neutron monitor. (bottom right) Ionospheric TEC observed at Fuzhou GNSS station.

The measurements provided by the above two networks mainly cover five solar-terrestrial areas: Sun/solar, cosmic rays, geomagnetic field, ionosphere, and the upper atmosphere. Some of the typical instruments include solar radio and optical telescopes, magnetometers, digital ionosondes, Global Navigation Satellite Systems (GNSS) receivers, incoherent scatter radars, mesosphere-stratosphere-troposphere radars, meteor radars, light detection and ranging, Fabry-Perot interferometers, and all-sky airglow imagers. Some of the latest data can be seen on the website of SEPC/NSSC (Figure 3).

Development of Operational Space Weather Models

NSSC has engaged in developing operational space weather models since its establishment to provide accurate and objective specification and forecasting of space weather [*Gong et al.*, 2014]. These models describe space weather phenomena covering solar and interplanetary, geomagnetic and magnetosphere, ionosphere, and thermosphere. Before an operational model is developed, real-time data availability for its input, time resolution and lead time of the forecast, and prediction horizon and accuracy of the model are assessed to make sure that it has potential to meet the users' requirements. After developed, the model will be verified and validated. Once the model passes the test stage, it can be integrated into the operational forecasting system and implemented very quickly in the space weather service.

After performing analysis of users' requirements as well as the assessment of scientific advances and existing space weather research models, we have identified about 20 operational models as high priorities for near-term needs. These models can be categorized into three groups: space weather events prediction (e.g., flares, SPE, and geomagnetic storms), space weather indices prediction (e.g., $F_{10.7}$, sunspot number, *Ap*, *Kp*, *Dst*, and *AE*), and space environment parameters prediction (e.g., energetic charged particle, plasma, and thermosphere density). Space weather event predictions, such as the occurrence probability of a severe solar proton event and major geomagnetic storm, are used for high-level decision-making by mission managers or ground- and space-based system operators. Space weather indices prediction provides a scaled level of the

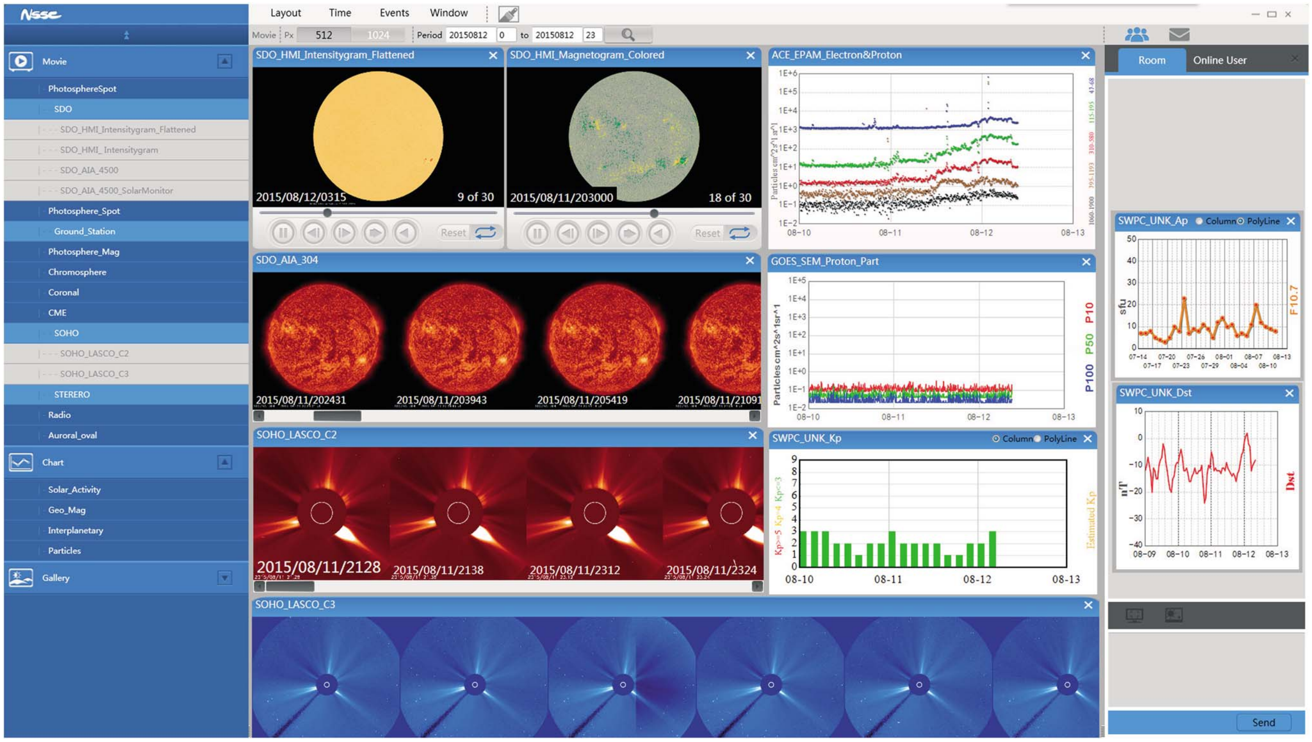

Figure 4. Interface of online analyzing tool.

overall activity and pending events. Prediction of space environment parameters provides spatial distribution and temporal evolution of particles or electromagnetic fields. Such parameters are used for detailed space environment effect evaluation.

The modeling efforts are carried out mainly in two approaches, under programs supported by several departments of China, including the State Administration of Science, Technology and Industry for National Defense and the Natural Science Foundation of China. One approach is to develop our own model from the ground up inside NSSC, and the other is to work cooperatively with other institutes or universities. Among the 20 operational models identified as of high priorities, currently, 10 models have been completed and applied to operational services, including solar cycle $F_{10.7}$ and sunspot predictions by similar cycle method (see *Wang et al.* [2008] and *Miao et al.* [2008] for the prediction of solar cycle 24), 27 day $F_{10.7}$ and *Ap* predictions by linear autoregressive method, *Kp* prediction by neural network, and *Dst* [*Wang et al.*, 2003], *AE* [*Luo et al.*, 2013], magnetopause [*Lin et al.*, 2010], relativistic electrons at the GEO orbit, and China total electron content (TEC) map predictions by empirical statistical modeling. Six models are still in the development stage, which are for predictions of coronal mass ejection propagation [*Shen et al.*, 2014], coronal hole high-speed streams [*Luo et al.*, 2008], plasma sheet [*Luo et al.*, 2011], regional TEC assimilation [*Aa et al.*, 2015], regional ionospheric index, and 400 km thermosphere mass density models [*Lei et al.*, 2012]. Two prediction models, for solar proton events and the radiation belt, are in a preliminary phase. Modeling efforts for regional geomagnetic disturbance and ionosphere scintillation will be carried out soon. Model results for the general public are published over the internet and updated automatically (http://eng.sepc.ac.cn). Some of the models targeting at customized users are integrated in our operational space weather forecasting system. These models have already been used for the services of China's space missions.

Space Environment System and Online Analyzing Tool

Operational Space Environment System in SEPC/NSSC works on integration of real-time monitor data, mature prediction models, effects analysis technology, and converting mature results of scientific research into services of space environment application. Consisting of data, model, analyze, product, and service subsystems, the operational system runs 24/7 and plays an important role in space environment service, including giving timely, accurate, and reliable nowcasts and forecasts, useful space environment effects evaluation, and the transition from innovative research models into operational applications.

In order to better help forecasters to make forecasts, SEPC/NSSC has developed and put into use an ancillary online analyzing software (Figure 4). It is named the Space Environment Analysis and T-Plot tool, which is designed based on innovative web service information technology. This software is customer configurable and adaptable, which can be used as a powerful decision-making and drawing tool. The space environment forecast results, which are implemented by the forecasters using the manual forecasting model, will be automatically evaluated and displayed by this tool. Moreover, forecasters can optionally assemble all kinds of space environment information and define personal interfaces with requested data for space environment analysis, forecast, and research through utilizing the function of historical data inquiry and space environment events statistical results inquiry. This online tool can provide abundant data resources and various analysis results in the form of charts, movies, reports, and statistical tables; the message board as well as the instant messenger are also integrated as the chat room service to strengthen the communication and information sharing between forecasters. Considering that this software provides convenient interaction between user and application, we aim to make it possible for both domestic and international space environment forecasters and/or researchers to have open access to this software in the web-based form, which is currently in the test phase and will be online soon.

Looking Forward

Services can be improved through applied research that focuses on the needs of an increasingly diverse user community. Efforts are being taken by SEPC/NSSC to improve understanding of user needs and to provide relevant, intelligible, and actionable products that users can fully understand and use easily. In China, space missions are on a path of sustained and rapid development. BeiDou Navigation Satellite System (COMPASS), China manned space flight missions, Lunar Explorations, and the Strategic Priority Program on Space Science require more relevant and specific space weather information for ensuring their safety and application performance. By working with the users, SEPC/NSSC seeks to better understand the effects of space weather on the specific technology of their missions and ultimately provide more relevant products for them.

It is our overarching goal to improve forecasting accuracy and lead time through space weather research and modeling. Although we have identified 20 operational models as high priorities in the near term, it does not mean that they are sufficient to meet the users' requirements. As the fundamental understanding of space weather and modeling techniques improve, it will help drive the necessary advances in modeling capability to support user needs. At SEPC/NSSC there exists a group continually focusing on space weather research and modeling. The main aim of this group is to develop and improve predictive models, either by research to operations transition, or by direct model development.

SEPC/NSSC seeks international collaboration on data sharing and model verification. It is well understood by many countries that space weather is a global issue, which can cause disruptions to critical human technologies on a regional, national, and even international scale. Space weather monitoring and forecasting should be regarded as a global challenge. As a member of the International Space Environment Service (ISES), SEPC/NSSC is always willing to share observations and research and to collaborate on real-time predictions with other space weather providers.

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Information discussed in the manuscript can be found at http://eng.sepc.ac.cn or by contacting the authors.

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