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Advancing the understanding of the Sun–Earth interaction—the Climate and Weather of the Sun–Earth System (CAWSES) II program

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Abstract

The Scientific Committee on Solar–Terrestrial Physics (SCOSTEP) of the International Council for Science (ICSU) implemented an international collaborative program called *Climate and Weather of the Sun–Earth System* (CAWSES), which was active from 2004 to 2008; this was followed by the CAWSES II program during the period of 2009–2013. The CAWSES program was aimed at improving the understanding of the coupled solar–terrestrial system, with special emphasis placed on the short-term (weather) and long-term (climate) variability of solar activities and their effects on and responses of Geospace and Earth's environment. Following the successful implementation of CAWSES, the CAWSES II program pursued four fundamental questions addressing the way in which the coupled Sun–Earth system operates over time scales ranging from minutes to millennia, namely, (1) *What are the solar influences on the Earth's climate?* (2) *How will Geospace respond to an altered climate?* (3) *How does short-term solar variability affect the Geospace environment?* and (4) *What is the Geospace response to variable inputs from the lower atmosphere?* In addition to these four major tasks, the SCOSTEP and CAWSES promoted E-science and informatics activities including the creation of scientific databases and their effective utilization in solar–terrestrial physics research. Capacity building activities were also enhanced during CAWSES II, and this represented an important contribution of SCOSTEP to the world's solar–terrestrial physics community. This introductory paper provides an overview of CAWSES II activities and serves as a preface to the dedicated review papers summarizing the achievements of the program's four task groups (TGs) and the E-science component.

Keywords: Coupled solar–terrestrial system; Solar activity; Space weather; Geospace; Atmospheric coupling; Trends; Global warming; Paleoclimatology

Introduction

A. Coupled solar–terrestrial system

The Sun, together with the Earth's motion along its orbit, govern changes in the solar–terrestrial environment on time scales ranging from minutes to glacial cycles. Changes in Earth's climate have been the focal point of recent research in the solar–terrestrial physics (STP) community, and a special emphasis has been placed on the coupling between the troposphere (below 10–15 km altitude), middle atmosphere (10–100 km altitude), and near-Earth Geospace (mesosphere, thermosphere, ionosphere, and magnetosphere), as well as on solar activity.

The Sun continuously provides solar radiation to the Earth, and there is considerable variation in the spectral density. This radiation is sporadically modified by flare events that affect the magnetosphere, thermosphere, and ionosphere. The quasi-steady flow of the solar wind is also modified by coronal mass ejections (CMEs), which accelerate energetic particles and cause geomagnetic storms during subsequent impacts on Earth. The energetic particle precipitation (EPP) leads to the modification of the ionosphere and neutral atmosphere. In addition, galactic cosmic

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rays (GCRs) also impinge into Earth's environment. Observations have suggested that energetic particle forcing may affect wave propagation, zonal mean temperatures, and zonal winds in the Northern Hemisphere winter stratosphere (Seppälä et al. 2013). However, the mechanisms by which these changes occur are still not known.

As changes in the Earth's atmosphere occur, whether due to changes in solar forcing or in response to enhanced anthropogenic activity and increased greenhouse gas (GHG) concentrations, the energy balance of the Earth's atmosphere is altered and this affects its dynamics. Specifically, changes can occur in the propagation of atmospheric gravity waves, planetary waves, and tides, which play important roles in driving the general circulation of the middle atmosphere.

Temporal variations within the coupled solar–terrestrial system ranging from minutes to millennia are summarized in Table 1. Short-term variability with time scales from minutes to weeks is represented by solar flares, CMEs, geomagnetic storms, and atmospheric waves. At longer time scales, there are periodic variations such as semi-annual or quasi-biennial oscillations and the 11-year solar cycle. Additionally, the Sun–Earth system is subjected to long-term changes in solar irradiance, ozone depletion, and in turn, climate change. Changes can occur at all spatial and temporal scales, as well as between and within different layers in the atmosphere, as a result of solar variability.

Understanding the coupled Sun–Earth system is both an essential and an urgent issue. Knowledge of the natural variability of the climate system and assessment of the changes caused by anthropogenic activity will allow for greater precision and confidence in predicting a unified framework for future climate. Research over previous decades has provided solid explanations for many of the individual processes involved in the coupling of the Sun–Earth environment, but a system-level approach is required in order to make progress at these scientific frontiers. The necessary infrastructure has been sufficiently developed over the years to make addressing these topics possible. Presently, the international research community has access to observations from every critical region of the space environment, and an operational framework within which these international comprehensive studies are conducted has been provided by the Scientific Committee on Solar–Terrestrial Physics (SCOSTEP).

B. A brief historic overview of the SCOSTEP's international collaborative programs

The accomplishments of the SCOSTEP are related to the international scientific programs on STP associated with the International Council of Science (ICSU) Unions and Associations. The history of STP research began just before the *International Geophysical Year* (IGY: 1957/1958) and continued through the *International Quiet Sun Year* (IQSY: 1964/1965). These programs led to the creation of the precursor of the SCOSTEP, the Special Committee on Solar–Terrestrial Physics.

The first international scientific program organized and conducted by the SCOSTEP was the *International Magnetospheric Study* (IMS: 1976–1979). During the IMS, observations taken by constellations of satellites, rockets, balloons, and aircraft were coordinated with those of a global network of ground-based and sea surface sites. Subsequently, a more focused program timed to capture solar activity at the peak of sunspot cycle 21 was developed during the *solar maximum year* (SMY: 1979–1981). The comprehensive international *Middle Atmosphere Program* (MAP: 1982–1985) followed the SMY activities. During MAP, the SCOSTEP led its scientific community into a coordinated exploration of the previously largely ignored region, Earth's "middle atmosphere."

The *Solar–Terrestrial Energy Program* (STEP: 1990–1995) was the SCOSTEP's effort to implement an "end-

Table 1 Examples of time-sorted phenomena within the solar–terrestrial system

Minutes to hours	Days to weeks	Months to years	Decades to centuries
Solar flares	Solar radiation	Solar cycles	Solar irradiance changes
CMEs (coronal mass ejections)	Emerging flux features	Solar dynamo	Earth surface temperature
Geomagnetic storms	Trapped particles	Solar wind variance	Ozone changes
Substorms	Magnetic clouds	Cosmic rays	Galactic cosmic rays
Ionospheric currents and structure	Geomagnetic storms	Middle atmosphere dynamics, temperature, and composition	Maunder minimum
Atmospheric gravity waves	Radiation belt dynamics	SAO (semi-annual oscillation) and QBO (quasi-biennial oscillation)	Climate change
Turbulence			
Reconnection			
Radiation belt enhancements			

to-end" international scientific program that tracked energy emitted from the Sun, its passage through interplanetary space, its merger into the magnetosphere, and continuous flows into the upper atmosphere (ionosphere and thermosphere), whereby it is finally distributed through the middle atmosphere. The main goal of STEP was to improve our understanding of the linked solar–terrestrial system, and the program successfully increased dialog between practitioners of different STP disciplines beyond what existed in previous campaigns; STEP was formally extended through 1997 so that its ground-based scientists could cooperate with the new *International Solar–Terrestrial Physics* (ISTP) satellite programs.

Subsequently, during 1998–2002, the SCOSTEP concentrated on four smaller programs pertaining to individual disciplines. These disciplines included solar physics in the *International Solar Cycle Study* (ISCS) program, middle atmosphere physics in the *Planetary Scale Mesopause Observing System* (PSMOS) program, and equatorial regions in the *Equatorial Processes Including Coupling* (EPIC) program. During the 1998–2002 period, the SCOSTEP sought to further the objectives of STEP through its *STEP—results, application, and modeling phase* (S-RAMP) program. For example, an event-oriented, multi-regional study referred to as the Space Weather Month (September 1999) was conducted by S-RAMP and the study employed the array of ISTP satellites that were still operational.

In 2004, the Climate and Weather of the Sun–Earth System (CAWSES) program began linking the world's scientists in a cooperative effort to study the entire interactive Sun–Earth system and improve the understanding of solar–terrestrial relations, which impact life and society. Special emphasis was put on the short-term (weather) and long-term (climate) variability of solar activity and its effects/responses in Geospace and Earth's environment. During this time, CAWSES provided both scientific motivation and applications for enhancing the understanding of variations in the Sun–Earth system. In recognition of the very impressive past activities and results obtained, the SCOSTEP made a concerted effort to utilize planned space missions, ground-based observations, theoretical modeling, and data analyses all aimed at understanding aspects of the Sun–Earth system. The CAWSES program was eventually aimed at mobilizing the international solar–terrestrial science community to fully utilize past, present, and future data, as well as to produce improvements in space weather forecasting and the design of space- and Earth-based technological systems that can help us to better understand the role of solar–terrestrial influences on global change. In 2009, CAWSES II was launched as the second phase (2009–2013) of the very successful CAWSES program (2004–2008).

CAWSES overview

A. CAWSES program during 2004–2008

The CAWSES program consisted of the following four major themes: (1) solar influence on climate; (2) space weather, science, and applications; (3) atmospheric coupling processes; and (4) climate of the Sun–Earth system.

(1) *Theme 1 "Solar Influence on Climate"* was concerned with investigating the effects of solar variability on the lower and middle atmosphere climate. Variations in solar spectral irradiance, solar energetic particles, and galactic cosmic rays were considered along with their impacts on the thermodynamic, dynamical, chemical, and microphysical structure of the atmosphere. A special emphasis was placed on the physical processes involved. The study of paleoclimates provided a historical context within the broader domain of extreme environments pertinent to the Sun–Earth system.
(2) *Theme 2 "Space Weather, Science, and Applications"* focused on the study of the science and applications of the short-term variations of the Sun. It included solar-related rapid phenomena such as solar flares, CMEs, magnetic storms, and substorms, as well as the ionospheric structures driven by internal atmospheric processes. These phenomena can affect satellites in orbit, interrupt telecommunications, and degrade power distribution systems. A deterministic model of the Sun–Earth system was developed for nowcasting and predictions of the conditions of Geospace in order to minimize the impacts of solar events on technology, human society, and all life.
(3) *Theme 3 "Atmospheric Coupling Processes"* was aimed at gaining greater understanding of the atmospheric coupling processes from below and above. Solar and magnetospheric inputs penetrate downward into the atmosphere, while tropospheric effects propagate upward to the thermosphere. These processes involve dynamic, radiative, and electrodynamic coupling as well as the transport of atmospheric constituents.
(4) *Theme 4 "Space Climatology"* focused on descriptions and improved understanding of the average properties and regular variations of the system, i.e., descriptions and analyses of the probabilities of extreme events and evaluations of long-term trends. As the range and amount of STP data grew, detailed analyses of the climatology of the Sun–Earth system become feasible. Relevant datasets were assembled and evaluated, and these were made available to scientists worldwide. The characteristics

of each type of data (accuracy, precision, etc.) were assessed and brought onto a common space–time domain so that individual variations could be interpreted in terms of different causes.

Key results from the CAWSES program were published in a number of papers, and some of these were presented at the International CAWSES Symposium held at Kyoto University, Japan, on October 23–27, 2007; selected papers were published in the monograph "*Climate and Weather of the Sun–Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium*" (Tsuda et al. 2009). National CAWSES-related programs were also actively and very successfully carried out in a number of countries, e.g., Japan, India, and Germany; results from the German CAWSES program were summarized by Lübken (2013). In particular, the first phase of CAWSES led to a significant improvement in our understanding of the solar influence on climate changes, effects of abrupt solar events on satellite missions in near-Earth orbit, and the coupling of atmospheric layers through dynamical, electromagnetic, and photo-chemical processes. It was recognized, however, that there was still much that needs to be achieved, and therefore, the SCOSTEP endorsed the continuation of the CAWSES program as CAWSES II during 2009–2013.

Figure 1 shows time variations of sun spot numbers (SSNs) and the disturbance storm time index (Dst) for solar cycles 22, 23, and 24. The CAWSES and CAWSES II programs were conducted during the decreasing phase of cycle 23 and the rising phase of cycle 24. By the time the CAWSES programs were carried out, a significant body of observations had been accumulated that indicated that global warming due to anthropogenic activities was taking place, and this led to the need for investigations of anthropogenic trends and their effects on the entire atmosphere. However, there is still controversy regarding the solar influence on long-term variations of climate, and hence, interest in this research in the context of the CAWSES and CAWSES II is rapidly expanding.

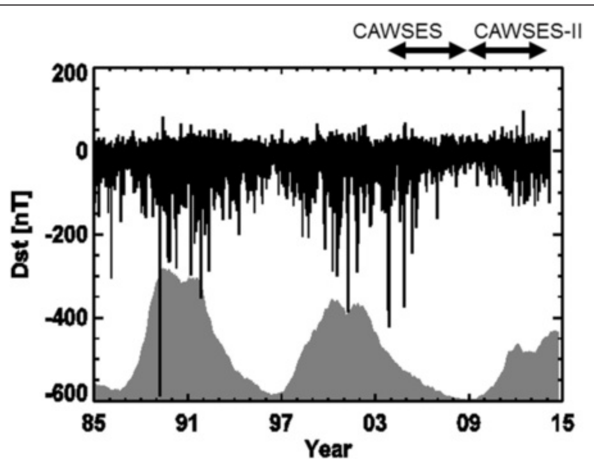

Fig. 1 Dst (*top*) and the daily sunspot number (SSN) for solar cycle 22–24. The *downward streaks* of Dst indicate major storms. The CAWSES project in 2004–2008 and CAWSES phase II in 2009–2013 were conducted during the decreasing and rising phases of solar cycles 23 and 24, respectively

B. CAWSES II: toward the solar maximum

Recognizing that some key questions on the coupling of the Sun–Earth system still remained unresolved after the completion of the CAWSES program, four major task groups (TGs) with associated objectives were developed for CAWSES II, as discussed below. Individual TG questions were subdivided into smaller topics and their investigation was pursued by coordinated interdisciplinary efforts.

TG1: What are the solar influences on the Earth's climate? Solar variability drives the Earth's environment on various time scales, and feedbacks are inherent in the Earth system, which may amplify the direct forcing effects from the Sun. The influence of this solar variability on Earth's climate is a key issue of the Intergovernmental Panel on Climate Change (IPCC), and one that continues to be highlighted by policy makers, climate change skeptics, and the media. The TG1 set out to answer the following questions:

What is the importance of spectral variations to solar influences on climate?
What is the effect of energetic particle forcing on the whole atmosphere and what are the implications for climate?
How well do models reproduce and predict solar irradiance and energetic particle influences on the atmosphere and climate?

TG2: How will Geospace respond to an altered climate? Radiative, chemical, and dynamical forcing from below contributes to disturbances of the upper atmosphere, which is defined as the mesosphere, the ionosphere, the thermosphere, and the exosphere. In response to rising GHG concentrations, cooling in the middle atmosphere (stratosphere) will alter the complex physical and chemical processes of this region. Rising GHG concentrations alter the ionosphere in a variety of ways and the effects could be transmitted to the magnetosphere, as will be described later in this report. Patterns of cooling and contraction of the upper atmosphere are emerging from model studies and observations, and these data are consistent with a strong connection to changes in the lower atmosphere. These changes may have unforeseen consequences for space-related technologies and societal infrastructures. The TG2 questions to be answered are as follows:

How do changes in tropospheric wave generation and their propagation through a changing atmosphere affect the dynamics of the mesosphere and lower thermosphere (MLT) region?
How do the MLT and higher regions respond to anthropogenic and natural changes?
Are the frequency of appearance and brightness trends of polar mesospheric clouds (PMCs) and noctilucent clouds (NLCs) due to changes in temperature and water vapor? Do frequencies and trends differ between the Northern and Southern Hemispheres?

TG3: How does short-term solar variability affect the Geospace environment?
Short-term solar variations directly and abruptly affect space weather. Flare electromagnetic radiation drives the ionosphere, while solar particulate outputs penetrate through space, interact with the magnetosphere and upper atmosphere, and even produce disturbances at Earth's surface. When CMEs impact the magnetosphere, a severe geomagnetic storm can lead to a number of responses in regions ranging from the magnetosphere to the Earth's surface. A systems approach is crucial for the understanding and forecasting these space weather events. Key topics of TG3 are as follows:

Origin and emergence of solar magnetism
Shock formation in the solar atmosphere
CME and interplanetary CME (ICME) connections
Coronal hole and high-speed solar wind
Three-dimensional (3-D) structure of ICMEs and solar wind
Solar wind and magnetosphere interface
Substorm variability and radiation belts

TG4: What is the Geospace response to variable inputs from the lower atmosphere?
A variety of new evidence suggests that tropospheric weather is an important ingredient in space weather. Equatorial ionospheric densities are modulated by atmospheric waves driven by persistent tropical rainstorms. Radio waves generated by lightning strikes in rainstorms interact with radiation belt particles to clear a "safe" zone between the inner and outer belts in the magnetosphere. Atmospheric gravity waves generated by hurricanes and typhoons may seed plasma bubbles in the low-latitude ionosphere. The extent to which the effects of this quiescent atmospheric variability are transmitted to the magnetosphere has yet to be resolved. The overall goal is to elucidate the dynamical coupling from the lower atmosphere to Geospace for various frequencies and scales such as gravity waves, tides, and planetary waves and for equatorial, middle, and high latitudes. The questions addressed by TG4 are as follows:

How do atmospheric waves connect tropospheric weather with ionosphere–thermosphere–magnetosphere (ITM) variability?
What is the relation between atmospheric waves and ionospheric instabilities?
How do the different types of atmospheric waves interact as they propagate through the middle atmosphere to the ionosphere?
How do thermospheric disturbances generated by auroral processes interact with the neutral and ionized atmosphere?
How do thunderstorm activities interact with the atmosphere, ionosphere, and magnetosphere?

Figure 2 shows the schematic relation between the four CAWSES II tasks for a coupled Sun–Earth system. In the CAWSES context, the SCOSTEP's capacity building and E-science activities are important features and these will be discussed shortly.

The successful implementation of CAWSES II depended on its programs and on its leadership, as summarized in Table 2.

Scientific achievements of CAWSES II

This section summarizes some key results and highlights of CAWSES II, as outlined in an overview lecture by the CAWSES II Co-chair T. Tsuda at the International CAWSES II symposium held at Nagoya University during November 18–22, 2013. Detailed reviews of the scientific achievements relevant to each TG can be found in Seppälä et al. (2014) for TG1, Laštovička et al. (2014) for TG2, Gopalswamy et al. (2015) for TG3, Oberheide et al. (2015) for TG4, and Fox and Kozyra (2015) for E-science.

A. TG1: Solar influence on the Earth's climate

Major sources of solar influences on climate are solar irradiance and EPP, which consist of solar proton events and other high-energy particles. Total solar irradiance (TSI) was included under the fourth assessment report (AR4) of the IPCC published in 2007, but it has become important to consider spectral variations of the solar irradiance as well, particularly large variations of the ultraviolet (UV) band. In addition to solar influences, research has shown that both galactic and solar cosmic rays (CRs), which have much higher

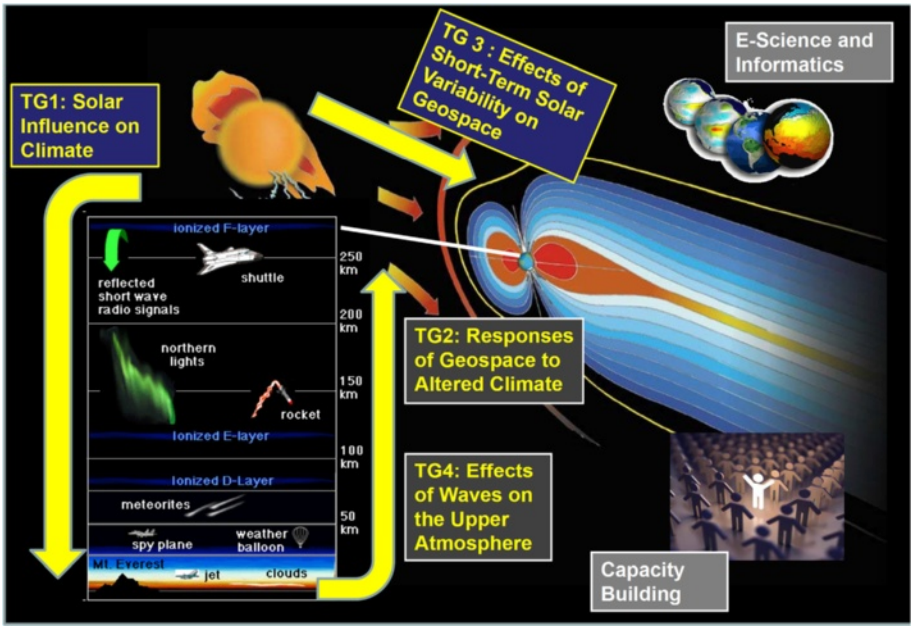

Fig. 2 Schematic concept of CAWSES II showing the four task groups (TGs), E-science, and capacity building

energy than EPPs, can affect Earth's climate. The TG1 focused on observational and modeling studies of the influence of solar radiation and energetic particle precipitation on the atmosphere and climate. Significant progress was achieved in recognizing the importance of solar forcing on climate by bringing together the following two international communities studying STP and stratospheric processes and their role in climate (SPARC), that is, *High-Energy Particle Precipitation in the Atmosphere* (HEPPA) and *Solar Influences for SPARC* (SOLARIS).

A-1 Solar irradiance

Solar influence on climate is now considered as an important contributor to climate variability. Research carried out during the CAWSES II period showed the importance of the solar spectral irradiance (SSI) in addition to the TSI (Ermolli et al. 2013), and the research focus has shifted from examining the global response to studying regional responses to variations in SSI and TSI. The TSI is the best known source of solar forcing into the Earth's atmosphere, and it impacts the surface directly by influencing the atmosphere above via the so called *bottom-up mechanism* (Gray et al. 2010). Briefly, solar radiation absorbed over the oceans leads to an increase in evaporation and moisture, which changes precipitation patterns and vertical motions, thus changing trade winds and ocean upwelling. However, global radiative forcing from TSI on a global mean basis has been estimated to be very small (0.05 Wm^{-2}), so the effects on global temperature are very small and cannot account for the observed overall warming trend in global mean air surface temperatures.

In the Earth's atmosphere, the SSI forcing plays a key role as the main driver in the so called *top-down mechanism* (Gray et al. 2010) by affecting the chemical-dynamical coupling of the stratosphere to the tropospheric climate via interactions with ozone. The top-down mechanism originates in the stratosphere, where UV radiation modulates local radiative heating at the tropical stratopause and ozone chemistry. In addition, the SSI directly impacts the UV photolysis of O_2, an important source of ozone in the stratosphere. Figure 3 shows the main features for both the bottom-up mechanism for TSI and the top-down mechanism for SSI (Seppälä et al. 2014). Improved TSI and SSI measurements and model simulations have shown the importance of the top-down stratospheric UV (SSI) mechanism and have led to more reliable solar cycle variation estimates. For example, the SSI-spectrum solar signal of O_3 has been simulated by various models and a new value for the solar constant was obtained as 1361 Wm^{-2}; this new value was used in the Fifth Coupled Model Intercomparison Project (CMIP5) of the IPCC fifth assessment report (AR5). The direct effects of SSI have also been investigated through determining ionization rates, chemical changes, and radiative effects.

A-2 Energetic particles

The process of EPP plays an important role in the energy and composition of the terrestrial atmosphere because it directly affects the ionization rates and causes chemical changes in NO_Y, O_3, and some other constituents. These

Table 2 Organizational structure of the CAWSES II governance

Co-chairs of CAWSES II	
	Susan Avery, Alan Rodger (2009–August 2011)
	Joseph Davila, Toshitaka Tsuda (October 2011–2013)
Task group (TG) leaders	
	TG1: Katja Matthes, Annika Seppälä (2009–2013),
	Joanna Haigh, Ilya Usoskin (2009–2011),
	Cora Randall (April 2012–2013)
	TG2: Dan Marsh, Jan Laštovička (2009–2013),
	Gufran Beig (April 2012–2013)
	TG3: Kazunary Shibata, Joseph Borovsky (2009–2013),
	Yihua Yan (April 2012–2013)
	TG4: Jens Oberheide, Kuzuo Shiokawa (2009–2013),
	Subramanian Gurubaran (April 2012–2013)
	E-Science and informatics: Peter Fox, Janet Kozyra
	(2009–2013)
Capacity building (SCOSTEP):	
President and vice president	Robert Vincent, Brigitte Schmieder (2009–2011)
	Nat Gopalswamy, Franz-Josef Lübken (2011–present)
Scientific secretary	Gang Lu (2009–2010)
	Marianna Shepherd (2010–present)

direct effects have been studied extensively through the HEPPA model–measurement intercomparison community effort. Funke et al. (2011) showed that EPP can induce changes in ozone, while Baumgaertner et al. (2011) showed that EPP–NO_X has an influence on winter temperature change.

Strong indirect effects of EPP on the stratosphere were also observed, thus showing the need for more studies of the effects on the troposphere and Earth's surface. Particular attention has been given to the impacts of solar protons on polar neutral atmospheric chemistry. So far, no long-term (multi-year) effects have been identified. However, there is growing recognition that we need to clarify the relative impacts of different particle sources such as auroral sources, medium energy electrons (MEEs), galactic cosmic rays (GCRs), solar energetic particles (SEPs), and recurrent energy particles (REPs).

Figure 4 summarizes the impacts of EPP and CRs on the atmosphere (Seppälä et al. 2014; this issue), and these impacts involve both transport processes and chemical constituents. The EPP ionization effects are concentrated in the polar region, where HOx and NOx are produced. Cosmic rays, including SEPs and GCRs, are the main source of ionization in the lower neutral atmosphere and ionization peaks at heights of 13–14 km. Observations have shown that the GCR flux increases by 15 % over the period of the solar cycle from the solar activity maximum to the solar activity minimum. However, no trends in GCRs over the last 50 years (based on neutron monitoring data) have been detected.

Cosmic leaving outdoor droplets (CLOUD) experiments that used the proton synchrotron at Conseil Européen pour la Recherche Nucléaire or European Council for Nuclear Research (CERN) have shown that GCRs stimulate aerosol nucleation at upper tropospheric temperatures. Coincident surface measurements of aerosol nucleation and ion contributions have been conducted and global models have begun to include GCR ionization in their simulations.

A-3 Modeling

The TSI and SSI also vary as a result of the solar cycle, and it is important that these variations are considered in climate models (e.g., TSI is included in IPCC simulations); however, more observations are needed to determine the solar cycle variations in the SSI. Modeling of the effects of TSI, SSI, and EPP on the Earth's atmosphere is a very complex task. An increasing number of observations and studies indicate that both bottom-up and top-down mechanisms need to be included to improve simulations of top-down mechanisms, EPP ionization rates, and calculations of chemical effects.

It is important to improve predictive skills for solar variability on decadal time scales. An important topic of investigation is to determine how representative the last three solar cycles were. It has also become necessary to study the "correct" SSI forcing to be used in models as well as the relative importance of top-down versus bottom-up coupling mechanisms. With new data from relevant studies, it is expected that it will become possible to predict future trends in solar irradiance and long-term solar effects on climate.

B. TG2: response of the mesosphere–thermosphere–ionosphere system to global change

Long-term trends in the mesosphere, thermosphere, and ionosphere are areas of research of increasing importance, both because they are sensitive indicators of climatic change and because they affect satellite-based technologies, which are increasingly important to modern life. Their study has been an important topic of TG2. The three following topics have been the focus of trend investigations.

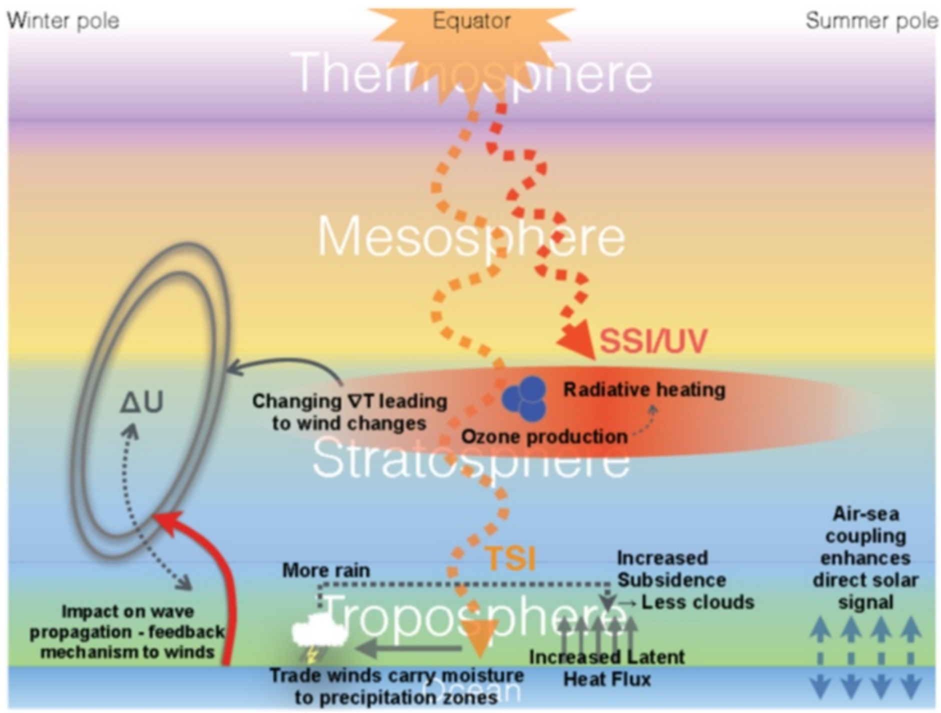

Fig. 3 Main features of the bottom-up and top-down mechanisms for TSI and SSI, respectively (Seppälä et al. 2014; this issue)

B-1 Changes in MLT dynamics

Stratospheric ozone recovery is producing temperature increases in the polar stratosphere and changes in the wind distribution, which modify gravity wave propagation into the mesosphere. The mesospheric residual mean circulation could be intensified by changes in the gravity wave drag, thus causing a negative temperature trend in the summer polar mesosphere.

Trends in planetary wave activity affect the winter stratopause height. In the Northern Hemisphere in winter, the stratopause height response to GHG increases differs from that in the Southern Hemisphere.

Long-term Fabry–Perot nightglow measurements over Arecibo, which are shown in Fig. 5, illustrate key trends in thermospheric neutral winds. Trends are strongly dependent (even as to the sign) on the day of year and the local time of night (Brum et al. 2012; Laštovička et al. 2014).

The effect of CO_2 doubling on the MLT dynamics was studied with a numerical simulation by using the National Center for Atmospheric Research (NCAR) thermosphere–ionosphere–mesosphere–electrodynamics general circulation model (TIME-GCM). Figure 6 shows the zonal wind change under solar minimum and geomagnetic quiet conditions at 0:00 UT (Laštovička et al. 2012). Considerable differences in wind amplitudes of up to 20 m/s were detected depending on latitudes and altitudes.

The trend drivers (GHGs, solar activity, geomagnetic variations, ozone, and water vapor) are themselves changing, and these changes need to be understood and quantified. It will also be necessary to define the trends in atmospheric dynamics, such as changes in circulation and wave activity patterns. The key challenges now are to improve the accuracy of various parameters and to reduce the differences in trends between models and observations. On a longer time scale, it will be necessary to combine our understanding of upper atmospheric trends and long-term changes in the stratosphere into one comprehensive scenario.

The impacts of long-term changes and trends on satellite-based technologies should also be investigated. In response to a cooling and contracting thermosphere resulting from decreased solar activity (Emmert et al. 2008; Emmert et al. 2010), the orbital lifetime of space debris has become longer. Hence, there are now more opportunities for collisions between satellites and dangerous space debris. Long-term changes in the total electron content (TEC) and gravity wave activity could also have an impact on the ionospheric influence on global navigation satellite systems (GNSSs) (e.g., GPS, GALILEO, GLONASS) in terms of signal propagation as well as ionospheric corrections and signal stability.

B-2 Trends in the mesosphere–lower thermosphere region

The first paper on upper atmosphere trends was published in 1989 (Roble and Dickinson 1989). Since then, our

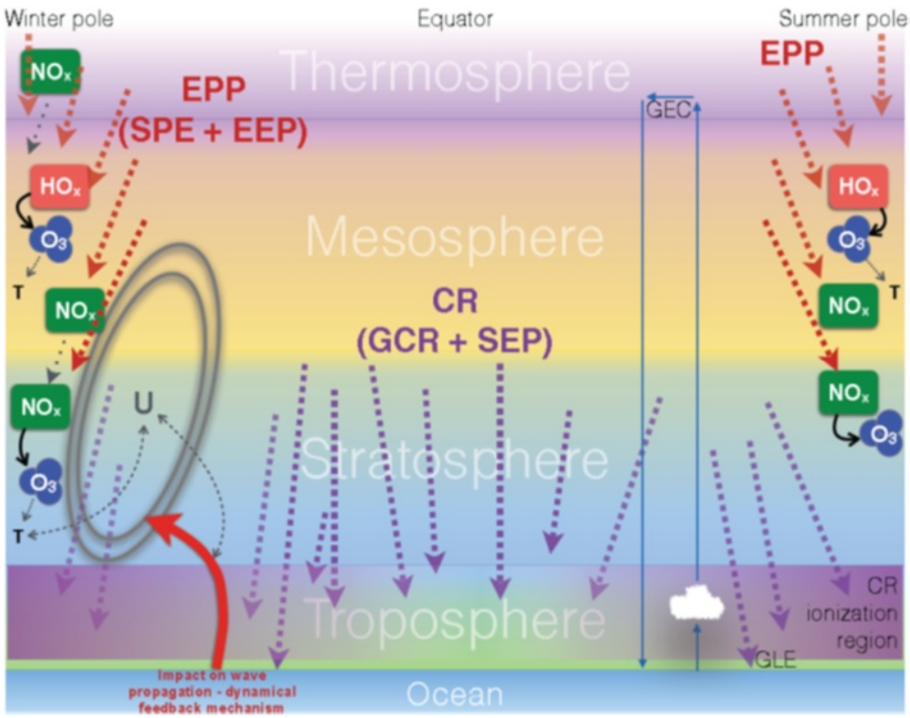

Fig. 4 Energetic particle precipitation (EPP) and cosmic ray (CR) impacts on the atmosphere (Seppälä et al. 2014; this issue)

knowledge and understanding of these trends have advanced considerably. The effects of anthropogenic GHG emissions are known to extend far from GHG sources, and these effects can be observed throughout the entire atmosphere. They cause warming in the troposphere but cooling in the upper atmosphere. However, GHGs such as CO_2, although major drivers, are not the only drivers of long-term changes and trends in the upper atmosphere and ionosphere. Anthropogenic induced changes in stratospheric ozone, long-term changes of geomagnetic

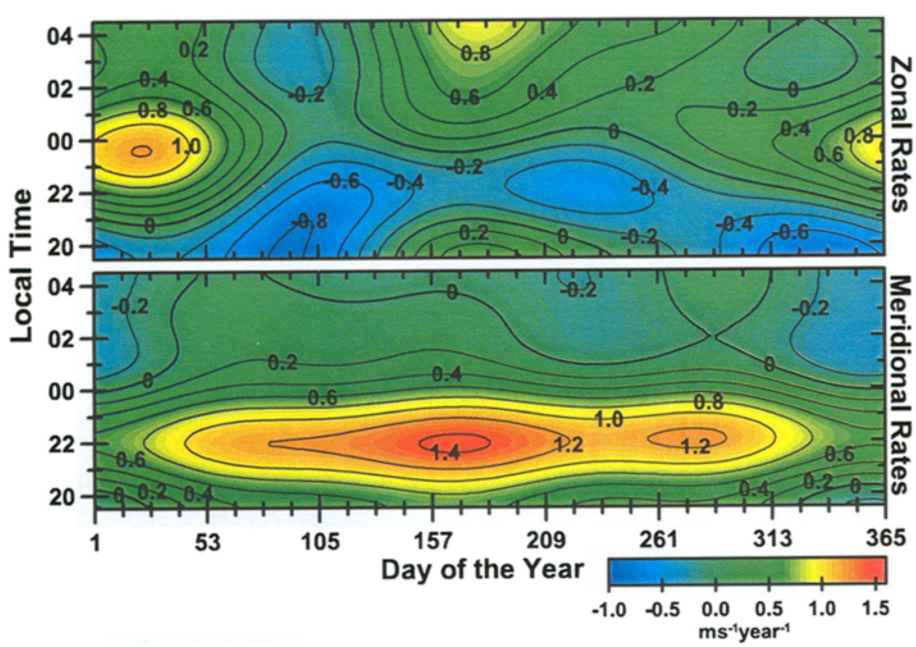

Fig. 5 Long-term trends in the thermospheric neutral winds over Arecibo from Fabry–Perot nightglow measurements (Brum et al. 2012)

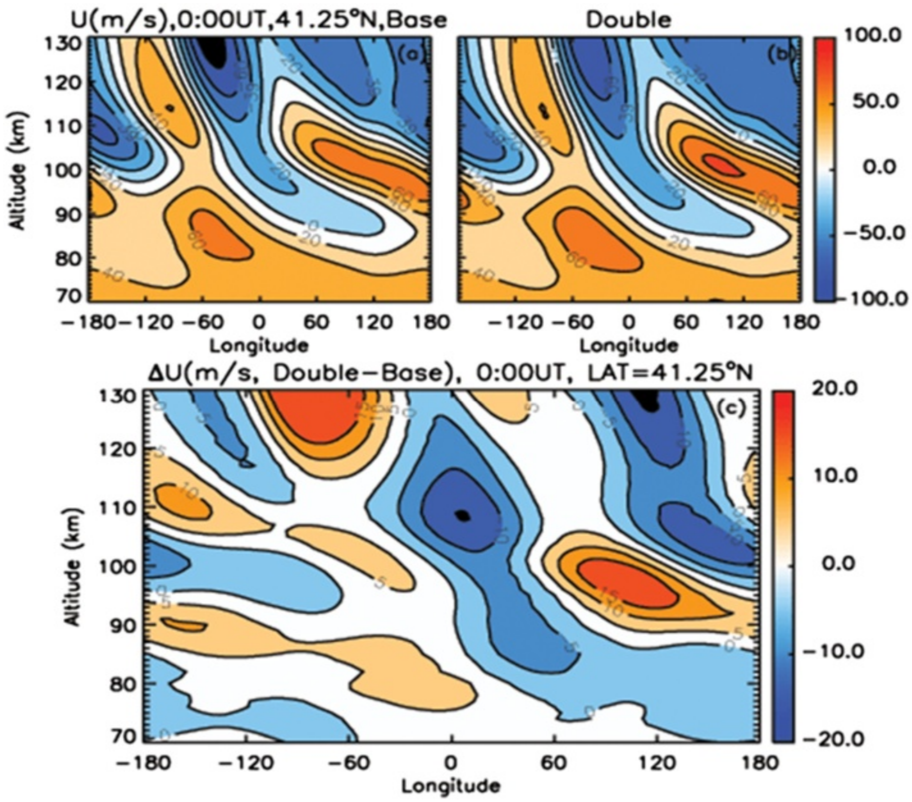

Fig. 6 The NCAR TIME-GCM model results for zonal wind. (*left*) Data for the base CO_2 case and (*right*) double CO_2 case at 41.25°N under solar minimum and geomagnetic quiet conditions at 0 UT. *Bottom panel* shows the change in the zonal wind between the two cases (Laštovička et al. 2012)

and solar activity, secular changes of the Earth's magnetic field, long-term changes in the activity of atmospheric waves (planetary, tidal, and gravity waves), and changes in water vapor concentrations also play a role, thus making the pattern of trends more complex and variable, as many trends change with time and location. Therefore, monitoring of long-term changes in various parameters and the separation and specification of the roles of various trend drivers are necessary.

Significant progress toward TG2 goals was reached in regards to the understanding and quantification of the role that stratospheric ozone changes play in trends in the upper atmosphere. A reasonable agreement between observed and simulated trends in mesospheric temperatures and polar mesospheric clouds was also achieved. Figure 7 shows the trends in the thermospheric neutral density near an altitude of 400 km, and the data were derived from satellite drag data over three solar cycles (Emmert et al. 2008). The observed trends were negative for any level of solar activity, but they were substantially stronger under solar minimum conditions, thereby implying a larger relative role for CO_2 in radiative cooling, which, however, has not been clarified yet.

As a result of collective scientific efforts toward understanding the trends in the upper atmosphere and ionosphere, knowledge of drivers has become more complete and some discrepancies have been removed or explained. The role of stratospheric ozone and recovery or leveling off of its declining trend in the mid- to late 1990s was proven to be significant, and its impacts on trends in the MLT and lower ionosphere have been to a great extent quantified.

A reasonable agreement between observations and simulations of trends in mesospheric temperatures and PMC albedo levels has also been achieved. Further, there is now a better understanding of why the thermospheric density trends are much stronger under solar cycle minimum conditions. A better understanding was also achieved in regards to the behavior of the upper atmosphere–ionosphere system during the extreme solar minimum 2008–2009 and its impact on long-term trends and their estimation.

B-3 Trends in PMCs and NLCs

More complete datasets have been accumulated, and this has led to new findings on trends. For example, a 33-year PMC data from the satellite solar backscatter ultraviolet (SBUV) instrument show significantly smaller trends than were previously published. Still, the data continue to

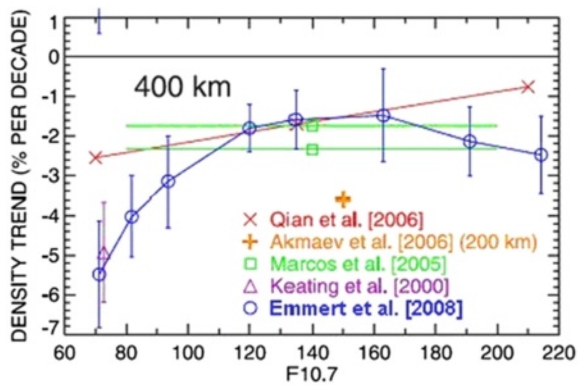

Fig. 7 Thermospheric neutral density trends near 400 km derived from satellite drag over three solar cycles (Emmert et al. 2008)

indicate a long-term increase in PMC brightness, particularly in the Northern Hemisphere.

A study of PMCs with the whole atmosphere community climate model (WACCM) has shown that relatively dim clouds should have different trends than the brighter clouds. Thus, a comparison of PMC data from different instruments needs to consider this "threshold effect." Models have shown that CO_2, CH_4, and chlorofluorocarbons (CFCs) drive mesospheric trends. Since about 1997, no significant trends have been found in mesospheric temperatures and PMC frequency, apparently because of the stabilization of stratospheric ozone. Inter-hemispheric coupling also has been observed, which involves a high correlation between the onset of the Antarctic PMC season and the time of breakdown of the stratospheric winter vortex.

C. TG3: effects of short-term solar variability on the Geospace environment

The TG3 has promoted coordinated observations, data analyses, and numerical modeling efforts in order to understand Earth-affecting solar and heliospheric events such as flares, CMEs, and coronal holes. Important results were obtained on the propagation of CMEs subject to interaction with coronal holes and other CMEs. In particular, the expanded field of view provided by the Solar TEerrestrial RElations Observatory (STEREO) observations helped scientists to track CMEs from their origin at the Sun throughout the heliosphere until they impacted Earth. The STEREO and Solar and Heliospheric Observatory (SOHO) white-light and extreme UV (EUV) observations were combined with interplanetary scintillation (IPS) observations, interplanetary radio burst observations from the National Aeronautics and Space Administration's (NASA's) WIND and STEREO missions, and in situ observations from the Advanced Composition Explorer (ACE) and WIND spacecraft to obtain a complete picture of these large-scale events. Shock-driving CMEs were studied based on radio observations, SEP acceleration, white-light shock structure, and in situ observations. Attempts were also made to characterize the state of the heliosphere based on in situ observations. Solar eruptions and their consequences were studied in the backdrop of the weak solar activity during solar cycle 24. The weak solar activity in cycle 24 has been attributed to the weak polar magnetic fields during solar cycle 23. This has led to discussions about the possibility of the Sun going through a grand minimum in the next few cycles. The responses of various Geospace layers to flares and CMEs were studied in great detail. The solar wind variability caused by the presence of low-latitude coronal holes on the Sun was also studied and comparisons were made between magnetospheric responses due to CME and co-rotating interaction region (CIR) structures. In particular, the difference in the magnetospheric particle populations was studied.

There have been significant advances in the study of auroral and plasma physics in the magnetosphere and in the polar ionosphere. For example, Tsurutani et al. (2014) reviewed characteristics of four major magnetic storm events during CAWSES II. Considerable progress also has been made in understanding the auroral patches in the diffuse aurora. The main driver of the auroral fragmentation has been identified as an instability that affects the balance between the earthward magnetic-tension force and the tailward pressure gradient force in the magnetosphere (Shiokawa et al. 2014).

C-1 Observations of solar eruptions

The leading structure of fast CMEs is the fast mode magneto-hydrodynamic (MHD) shock. There have been a number of intense studies to understand the leading shock from EUV observations obtained by the SOHO and STEREO experiments. Additionally, ground-based H-alpha observations have provided information on these shocks that have manifested as Moreton waves. Observations by the Solar Magnetic Activity Research Telescope (SMART) suggest that the fast EUV wave is basically the same as a Moreton wave (i.e., MHD shock), whereas the slow EUV waves are examples of pattern propagation. A combination of the EUV and white-light observations made by STEREO helped identify the height of shock formation in the corona, which seems to be typically about 0.5 solar radii above the solar surface. The white-light shock structure has been useful in studying the shock dynamics and deriving the magnetic field in the ambient corona and interplanetary medium. Shocks have been inferred from type II radio bursts in the corona and interplanetary medium, and it has been found that some of them die off before reaching 1 AU.

C-2 CMEs and ICMEs

The three-part structure of CMEs near the Sun has been identified at 1 AU in plasma data. Advanced modeling for solar eruptions and CMEs has been developed and 3-D MHD modeling was carried out for the solar wind structures associated with CMEs. Statistical studies were performed on the relation between CMEs and their ICMEs using charge state measurements. These studies suggest that all ICMEs may have a flux-rope structure, but the observational manifestation depends on the viewing geometry.

The ICMEs have been found to coalesce with other ICMEs and high-speed streams and CIRs. Multiple eruptions from the same region on the Sun have been found to result in a very complex solar wind, which leads in turn to both deflection and retardation of ICME propagation. These large-scale interactions have helped us to understand deviations from expected arrival times of Earth-directed CMEs. The ICMEs that arrive close to Earth cause Forbush decreases. New investigations have also shown that halo CMEs are the most effective population for causing Forbush decreases.

C-3 Coronal holes and CIRs

High-speed streams (HSSs) originating from coronal holes form CIRs when they collide with the slower solar wind ahead. The compressed interaction region contains a southward pointing magnetic field, and geomagnetic activity ensues. The geomagnetic storms caused by CIRs are generally weaker compared to those caused by CMEs. Comparisons made between periods of weak and strong HSSs have shown that the ring current was stronger and the magnetospheric electron flux was higher in the strong HSSs. The differing physical conditions in the magnetosphere under weak and strong HSSs have also been reported to result in different evolutions of magnetospheric particle flux. The ionospheric response to the weak CIRs has been found to be marginal but observable, while the thermospheric density response has been reported to be distinct at an altitude of 400 km above the ground.

The CMEs and CIRs (also HSSs) have been shown to result in different developments of various current systems and geomagnetic activity within the Earth's magnetosphere and ionosphere. Superposed-epoch analyses of CME-driven and CIR-driven storms have shown different evolutions of certain physical parameters in the two types of geomagnetic storms. For example, the ion temperature increased in the recovery phase of CIR storms, while it increased rapidly at the onset of CME storms and cooled off during the main phase.

C-4 Solar energetic particle events

The STEREO spacecraft were launched in October 2006, but large SEP events started occurring only toward the end of 2010, thus boosting SEP studies during CAWSES II. From then on, there were many SEP events that have been studied extensively. The STEREO particle detectors, together with those at Sun–Earth L1, have provided information on the longitudinal distribution of SEP intensity. The Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) spacecraft data have helped us to understand the radial variation of SEP intensity. Specifically, these observations allowed us to estimate the longitudinal extent of SEP events throughout the heliosphere. The STEREO instruments observed the July 23, 2012 extreme SEP event, which has been extensively studied in comparison with the Carrington 1859 eruption.

In addition to the well-known longitudinal connectivity required between the observer and the solar source, it was found that a stringent latitudinal connectivity may be needed for an SEP event to be detected at GeV energies (e.g., ground level enhancement events). This has led to a new paradigm regarding the spatial distribution of the acceleration region in a shock. It has been suggested that the highest energy particles may be accelerated near the nose of the shock.

C-5 Peculiar behavior of the solar activity during cycle 24

Solar activity was at an unprecedented low level when the CAWSES II program started. Its mandate was to study the evolution of the Sun toward the maximum phase of solar cycle 24. It turned out that the maximum phase was very weak with a 45 % reduction in the sunspot number compared to solar cycle 23. There has been an intense focus on the origin and consequences of the weak activity, given that it was the weakest in the Space Era. The weak activity has been attributed to the weak polar fields observed during cycle 23. The arrival of the solar maximum was different in the two solar hemispheres, and it was marked by the appearance of high-latitude prominence eruptions and polar field strength values close to zero. The polarity reversal was also fluctuating and asymmetric. The weak activity resulted in a reduced density magnetic field and Alfven speeds in the heliosphere, as inferred from measurements made at 1 AU by spacecraft such as ACE, WIND, and SOHO. One of the consequences of the weak state of the heliosphere has been the change in physical properties of CMEs in cycle 24, which has produced the current mild space weather, i.e., lack of major geomagnetic storms (see Fig. 1) and high-energy SEP events (see Fig. 8).

Figure 8 shows large SEP events with energies >10 MeV since 1976 for solar cycles 21–24. It has been found that the number of large SEP events did not decrease significantly during cycle 24. However, the number of high-energy (>500 MeV) SEP events was very small in cycle 24. In particular, the number of ground level enhancement events (~GeV particles arriving at Earth's troposphere) was only 2, compared to 16 in cycle 23.

D. TG4: geospace response to variable inputs from the lower atmosphere

The recent advent of new satellite missions, ground-based instrumentation networks, and the development of whole atmosphere models has resulted in a major shift in our understanding of the variability of Geospace, where atmosphere–ionosphere–magnetosphere interactions occur.

It is now realized that conditions in Geospace are linked strongly to terrestrial weather and the climate below, although it was previously thought that the near-Earth space environment was driven only by energy injections at high latitudes connected via magnetosphere–ionosphere coupling and solar radiation at EUV wavelengths. The primary mechanism through which energy and momentum are transferred from the lower atmosphere is through the generation and propagation of atmospheric waves over a wide range of spatial and temporal scales; this includes electrodynamic coupling through dynamo processes and plasma bubble seeding. Studies on the Geospace response to waves generated by meteorological events, their interaction with the mean flow, and their impact on the ionosphere were the main subjects of TG4. The role of gravity waves, planetary waves, and tides, and their ionospheric impacts have been closely examined through addressing the following key topics.

D-1 Atmospheric gravity waves

It has been found that there is a significant penetration of atmospheric waves into the ionosphere over a wide frequency range. Figure 9 shows schematics of upward propagating gravity waves from the troposphere and their interaction with the ionospheric plasma. Some waves, on attaining unstable amplitudes or encountering critical levels near the mesopause, break and release momentum flux, which causes secondary waves that penetrate further into the thermosphere. Gravity waves in the thermosphere can then act as potential triggers for Rayleigh–Taylor type plasma instability in the equatorial and mid-latitude ionosphere, for which the polarization electric field amplifies the inhomogeneity of ionospheric conductivity by moving plasma vertically through the *E*x*B* drift. An initial perturbation can thus grow to a medium-scale traveling ionospheric disturbance and large-scale plasma bubble; the latter affects satellite communications and navigation technology and plays a major role in determining the space weather at low latitudes.

By using the GPS-TEC measurement network, a peculiar event of acoustic and gravity wave penetration into the ionosphere was observed as a result of the tsunami associated with the gigantic earthquake in Japan in March 2011 (Tsugawa et al. 2011). Gravity waves also can seed the ionospheric Rayleigh–Taylor instability, thus causing plasma bubbles and equatorial spread F.

D-2 Atmospheric tides and planetary waves

Longitudinal variations in the thermosphere with zonal wavenumber 4 are related to non-migrating tides generated by tropospheric convection activity. Figure 10 shows schematics of tidal coupling from the troposphere into the ionosphere. Latent heat release in deep tropical convective clouds excites a series of non-migrating tides,

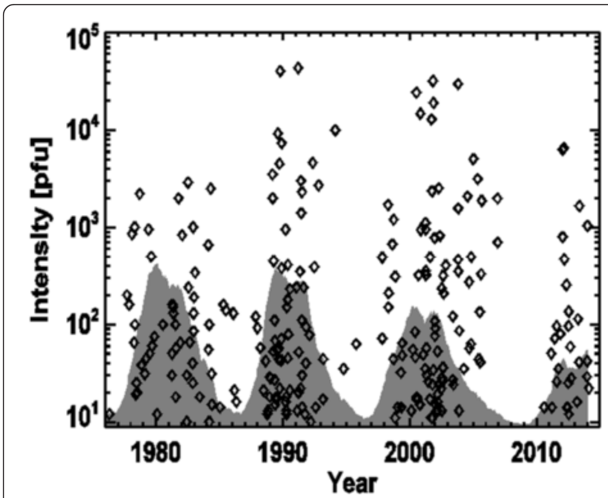

Fig. 8 Large SEP events (*diamonds*) with energies >10 MeV since 1976 covering solar cycles 21–24. The daily SSN is in *gray*

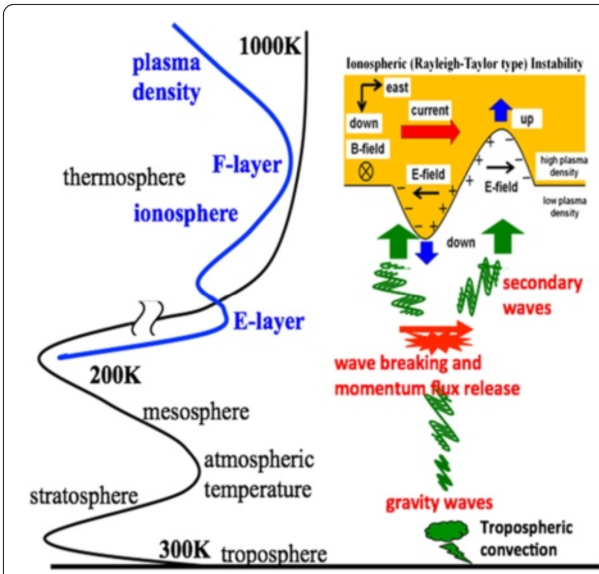

Fig. 9 Schematics of upward propagating gravity waves from the troposphere and their interaction with ionospheric plasma

and this results in large zonal wind modulations in the ionospheric E-region. An electromotive force is thus created with ensuing electric currents and polarization electric fields that are further transmitted along magnetic field lines into the overlying F-region where the resulting vertical ion drifts cause the apparent four-peaked longitudinal variation of the equatorial ionization anomaly. The data shown are diagnostics from the International Satellite Cloud Climatology Project (ISCCP), the Thermosphere, Ionosphere, Mesosphere Energetics, and Dynamics (TIMED) Doppler Interferometer (Oberheide et al. 2006), and the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite (Immel et al. 2006).

D-3 Coupling between different atmospheric regions

The TG4 activities have also been directed toward the study of the Geospace system and atmosphere–ionosphere–magnetosphere interactions in efforts to address the scientific challenges associated with resolving the system response to variable forcing and to unravel the processes leading to the observed mean state and variability of the ionosphere–thermosphere system (IT system). The advent of some satellite missions, ground-based instrumentation, and the development of whole atmosphere models has led to a paradigm shift during the CAWSES period that highlights the importance of the lower atmosphere (weather, stratosphere, etc.) in the coupling of the atmosphere.

The TG4 also directed efforts to understand how thermospheric disturbances generated by auroral processes interact with the neutral and ionized atmosphere. This is a competing effect to the inputs from the lower atmosphere in comparison to the solar influence, and it should be investigated more thoroughly under the unusually low solar activity during solar cycle 24.

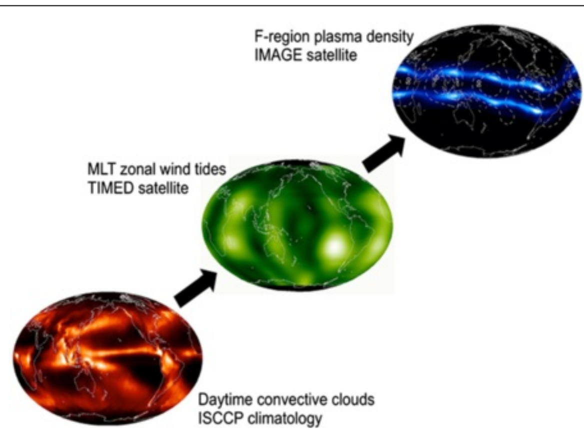

Fig. 10 Schematics of tidal coupling from the troposphere into the ionosphere. (*bottom*) Distribution of deep convective clouds, (*middle*) tidal zonal winds, and (*top*) F-region plasma density

The TG4 has promoted some observation campaigns such as the LOngitudinal NETwork (LONET), stratospheric warming (StratWarm), and various tidal campaigns (http://www.cawses.org/wiki/index.php/Task_4). In addition, TG4 has brought together the (neutral) atmosphere and plasma communities in order to jointly create a better understanding of how the atmospheric waves originating in the lower atmosphere impact the upper atmosphere. As a result, it is now possible to separate ionospheric variability caused by driving forces from below as compared to that from Sun.

E. E-science and informatics

A virtual institute concept was developed as a pilot study to utilize the ICT infrastructure to promote interdisciplinary studies under CAWSES II. This virtual institute provides access to scientific publications and databases in other discipline areas, thus enhancing interaction between various scientific communities that are pursuing science on a common theme with different basic principles and methodologies. The virtual institute has attracted worldwide attention in regard to the data-related aspects of its international collaborations and for promoting the sharing of localized datasets while establishing synergies with the World Data System (WDS). A WIKI[1] was established for CAWSES II (http://www.cawses.org/wiki/index.php/Main_Page), which is used to support science collaborations and outreach tasks. Capacity building has also been accelerated by interfacing with young scientists and students across national boundaries.

Capacity building—future solar terrestrial science

An important part of the CAWSES program has been the training and support for young researchers (graduate students, post-doctoral fellows) and early career scientists. To date, CAWSES has succeeded not only in expanding the frontiers of knowledge but also in building scientific capacity in developing countries. During the period of 2010–2013, the SCOSTEP/CAWSES II supported a total of 29 conferences, workshops, and science schools, as listed in Table 3.

Among those meetings were two flare monitoring telescope (FMT) workshops in Peru and Japan. The first FMT data analysis workshop at the University of Ica in Peru was held in November 2010 to educate young students and researchers how to analyze solar data taken by the FMT and to show them how to use a spectroscope for solar observations (http://esi.igp.gob.pe/FMTworkshop/). A second FMT workshop titled "Japan-Peru: FMT Summer School and Data Analysis Workshop" was held in July 2011 at the Hida Observatory, Kyoto University, Japan, and the National Astronomical Observatory of

Japan (NAOJ). Lectures were given on solar physics, space weather, and solar active phenomena especially related to the FMT. There were also tutorials on how to access (download) and analyze solar observational data, not only those obtained by the FMT but also data obtained by other ground-based and space-born instruments. In turn, these events stimulated students and young researchers to write scientific papers by analyzing such observations (http://cawses-ii-wg3.blogspot.com/2011/07/chain-peru-japan-fmt-workshop-hida.html).

Another good example of CAWSES II capacity building is the first TOSCA/COST ("Towards a more complete assessment of the impact of solar variability on the Earth's climate"/Cooperation in Science and Technology) training school in Thessaloniki (Greece), which was based on the successful format of the SCOSTEP's capacity building schools. The objective of this multidisciplinary event was to give young scientists a global understanding of the topical but also controversial role of solar variability in climate change.

Table 3 List of SCOSTEP/CAWSES conferences, workshops, and space science schools held during 2010–2013

2010	July 12–16	12th Solar Terrestrial Physics Conference, Berlin (Germany)
	March 8–9	1st Regional CAWSES II MLT Radar Workshop (Singapore)
	June 15–18	6th IAGA/ICMA/TG2 Workshop "Long-Term Changes and Trends in the Atmosphere," Boulder, Colorado (USA)
	November 22–26	First Latin American FMT Workshop, Ica (Peru)
	November 15–24	International School on Atmosphere–ionosphere Radars and Radio Sounding: Science and Applications (Taiwan)
2011	January 16–21	4th International Space Climate Symposium, Goa (India)
	February 14–18	4th IAGA/ICMA/TG4 Workshop on Vertical Coupling in the Atmosphere/Ionosphere System, Prague (Czech Republic)
	February 28–March 4	Chapman Conference on Atmospheric Gravity Waves and Their Effects on General Circulation and Climate, Honolulu (USA)
	June 6–10	3rd Workshop on Solar Influences on the Magnetosphere, Ionosphere, and Atmosphere, Sozopol (Bulgaria)
	July 20–31	FTM-2 Workshop, Kyoto/Hida Observatory (Japan)
	October 24–27	10th Layered Phenomena of the Mesopause Region, Blacksburg, Virginia (USA)
	November 7–11	2nd LISN Workshop, São José dos Campos (Brazil)
2012	March 12–16	13th International Symposium on Equatorial Aeronomy, ISEA13, Paracas (Peru)
	March 19–23	The MST13 Workshop, Kühlungsborn (Germany)
	May 3–4	2nd CAWSES II TG2 Workshop: Modeling Polar Mesospheric Cloud Trends Laboratory for Atmospheric and Space Physics, Boulder, Colorado (USA)
	Jul 14–22	Whole Atmosphere Wave Coupling and Interaction Processes (C22), 39th COSPAR, Mysore (India)
	Jul 9–14	Space Festival 2012, Coimbatore (India)
	September 11–14	7th IAGA/ICMA, Workshop on Long-Term Changes and Trends in the Atmosphere, Buenos Aires (Argentina)
	September 9–12	HEPPA/SOLARIS-2012 Workshop, Boulder, Colorado (USA)
	November 6–9	International Symposium on Solar–Terrestrial Physics (ISSTP 2012), Pune (India)
	November 12–16	Chapman Conference on Longitudinal and Hemispheric Dependence of Space Weather, Addis Ababa (Ethiopia)
2013	March 11–15	TOSCA Science School, Thessaloniki (Greece)
	June 10–14	IAUS300, Nature of Solar Prominences and Their Role in Space Weather, Paris (France)
	June 17–20	International Study of Earth-Affecting Solar Transients (ISEST) Workshop, Hvar (Croatia)
	June 24–28	AOGS 2013, CAWSES II Session, Brisbane (Australia)
	June 15–19	5th International Space Climate Symposium, Oulu (Finland)
	July 14–17	Workshop on Whole Atmosphere Coupling during Solar Cycle 24, National Central University, Jhongli (Taiwan)
	August 26–31	IAGA 2013, 12th Assembly, Mérida, Yucatán (México)
	November 18–22	International CAWSES II Symposium, Nagoya (Japan)

The main role of TOSCA has been to foster interactions between different communities. The TOSCA program is a pan-European effort to bring together over 70 leading European scientists with the aim of making progress on the scientific understanding of the Sun–climate connection. This connection is a typical example wherein progress has been hampered by the lack of interaction between various scientific communities. For that reason, the multidisciplinary program of this school has addressed various aspects of the Sun–Earth system, where emphasis is placed on the need for a global view of the system.

As part of the capacity building effort, the SCOSTEP educational comic books have reached young people in many countries, and the SCOSTEP continues to encourage more countries to translate the comics into their native languages. The comic books in English, French, German, Hindi, Italian, Russian, Spanish, and Tamil are now available.

Summary

A. Achievements of CAWSES II

The CAWSES II program has been aimed at studying the coupling processes involved in the solar–terrestrial system, the energy inputs to the Earth, the responses of Geospace, as well as the responses of the middle atmosphere and troposphere to energy inputs that vary on long and short time scales. Geospace solar radiation was investigated in terms of the solar spectral irradiance, in addition to the conventional total solar irradiance. One of the important tasks remaining is to determine how the different solar forcing contributions will develop in the future. Some predictions suggest a potential near-future grand solar minimum, like the Maunder minimum. New evidence suggests that there will be large, abrupt changes in atmospheric dynamics closely linked to regional-scale climate, similar to grand minima in the past. It is now evident that there is a need for a better understanding of the role of the Sun and all forms of solar forcing on continental- and subcontinental-scale climate.

The main driver of trends in the middle atmosphere and thermosphere/ionosphere, the concentration of CO_2, is continuously increasing. However, other trend drivers are mostly temporally and spatially reversible, like ozone. The role and behavior of these trend drivers have been to a substantial degree quantified, particularly in the case of stratospheric ozone. Trends in thermospheric densities result in increasing orbital lifetimes of dangerous space debris, thereby increasing the risk of damaging collisions with satellites. Reasonable agreement between the observed and simulated trends in mesospheric temperatures has been reached. The reversal of the ozone trend significantly changed the trend in mesospheric and mesopause-region temperatures. As for PMC trends, good agreement between observational and simulated trends was achieved. Model simulations indicate that dim PMCs should have different trends than brighter PMCs. The key open issue is the lack of knowledge on trends in atmospheric circulation, which are responsible for coupling with the lower atmosphere, and related trends in the upper atmospheric circulation. It is also important to quantify the trends more accurately and reduce the difference between observed and simulated trends. On longer time scales, a very important task will be to try to jointly model trends in the mesosphere and thermosphere with trends in the stratosphere, i.e., developing one holistic unified framework.

The short-term variability of the Sun manifested as flares and CMEs is the primary source of space weather. There has been significant progress made toward understanding the propagation of CMEs in the interplanetary medium as they interact with other large-scale structures. Significant progress on magneto-hydrodynamic models such as ENLIL has made it possible to predict the arrival time of CMEs at Earth, so the onset of geomagnetic storms and their sudden commencement, the generation of energetic storm particles, and Forbush decreases can be predicted to a reasonable degree of accuracy. Attempts are now underway to predict the intensity of solar energetic particles based on modeling CME-driven shocks. New discoveries were made during the CAWSES II period regarding the distribution of energetic particles in the heliosphere, thanks to the availability of instruments along and off the Sun–Earth line. New insights have been developed on the spatial location where the highest energy particles are accelerated based on the latitudinal connectivity constraints during energetic particle events. The impact of solar cycle variability on space weather was also studied extensively because of the opportunity provided by the weak solar cycle. It has been realized that a combination of weak solar activity and the resulting state of the heliosphere affects space weather events. Studies involving CMEs and ICMEs have arrived at the conclusion that all ICMEs may have a flux-rope structure. This is a significant result, which can help make predictions of the internal structure of ICMEs when they arrive at Earth. The internal structure of ICMEs, especially the southward magnetic component, is the key to predicting the strength and duration of geomagnetic storms. We are still a long way away in predicting the southward component based on solar observations. The new results obtained through comparisons of CIR and CME storms have provided fresh inputs to aid in the understanding of magnetospheric particles based on the waves generated under storm conditions.

Solar radiation actively generates atmospheric disturbances near the Earth's surface. These disturbances further excite various types of atmospheric waves, which propagate upward carrying energy and momentum. The behavior of the atmospheric gravity waves, planetary waves, and tides, which propagate from the lower atmosphere to the middle atmosphere and the ionosphere, was of a particular interest. Planetary waves seem to propagate into the thermosphere, thus modulating the E-region ionospheric dynamo by enhancing the amplitudes of semi-diurnal tides, and in turn, this modulates vertical plasma drifts and plasma density in the F-region ionosphere. The effect of sudden stratospheric warming on the thermosphere/ionosphere indicates coupling between the lower and upper atmosphere through planetary waves (Jin et al. 2012).

The results of various studies show significant penetration of atmospheric waves into the ionosphere in all frequency ranges, i.e., acoustic waves, gravity waves, tides, and planetary waves. We need to study the relative importance between (1) direct penetration of atmospheric waves into the thermosphere and then into the ionosphere and (2) electromagnetic coupling from the E- to F-region. Considering the low solar activity during solar cycle 24, its impact needs to be further investigated by examining, for example, the enhanced wave effects due to the cooler thermosphere, reduced wave dissipation, and less solar induced disturbances. This research over the next few years will allow us to determine the relative importance of waves (compared to the Sun) during high solar activity.

B. VarSITI: SCOSTEP's new program beyond 2014

Much progress was gained during the pursuit of questions that formed the basis of CAWSES II. However, it is now becoming more and more important to study an end-to-end coupled Sun–Earth system. Therefore, following the highly successful CAWSES II program, a new 5-year program in 2014–2018 called *Variability of the Sun and Its Terrestrial Impact* (VarSITI) was launched in January 2014.

The VarSITI program focuses on the declining phase of solar cycle 24 and its consequences in interplanetary space, Geospace, and Earth's atmosphere. The VarSITI program was established through a collective effort by the international STP community. White papers were solicited from international, interdisciplinary programs that could produce significant results in 4–5 years. In response to the solicitation, nine white papers were received by the end of 2012. The International Space Science Institute (ISSI) in Bern established a forum consisting of 27 international experts (including members of the SCOSTEP Bureau and white-paper authors) to brainstorm on the new scientific program during May 7–8, 2013. The ISSI forum defined the new scientific program and named it VarSITI. The new program focuses on the following four new major themes: solar magnetism and extreme events, Earth-impacting solar transients, magnetospheric changes, and consequences and processes in Earth's atmosphere. In order to make progress on these themes, four scientific projects have been defined, which are headed by international experts, i.e., Solar Evolution and Extrema (SEE), International Study of Earth-Affecting Solar Transients (ISEST)/Mini-Max24, specification and prediction of the coupled inner-magnetospheric environment (SPeCIMEN), and the role of the Sun and the middle atmosphere/thermosphere/ionosphere in climate (ROSMIC).

Collaborative activities are being planned to identify suitable existing WDS members to archive data acquired under the VarSITI program and to jointly promote data-oriented workshops and symposia that will aid international modeling efforts to understand solar terrestrial processes. During the CAWSES program, there were attempts to promote E-science for easy access to solar terrestrial data. The collaboration with WDS will fulfill the E-science role for the VarSITI program. The VarSITI program has great synergy with WDS, and both will benefit from the international collaborative efforts that will enhance the science returns from the data sources available at WDS. The collaboration will also promote global cooperation in solar terrestrial research through the use of observational data, models, and theory developed from all over the world.

Endnotes

[1]A WIKI is an application, typically a web application, which allows collaborative modification, extensions, or deletions of its content and structure.

Abbreviations

3-D: three-dimensional; ACE: advanced composition explorer; AOGS: Asia Oceania Geosciences Society; AR4: fourth assessment report; AR5: fifth assessment report; CAWSES: Climate and Weather of the Sun–Earth System; CERN: Conseil Européen pour la Recherche Nucléaire, or European Council for Nuclear Research; CFC: chlorofluorocarbon; CHAIN: Continuous H Alpha Imaging Network; CIR: co-rotating interaction region; CLOUD: cosmic leaving outdoor droplets; CME: coronal mass ejection; CMIP5: Fifth Coupled Model Intercomparison Project; COST: Cooperation in Science and Technology; CR: cosmic ray; Dst: disturbance storm time index; ENLIL: a time-dependent 3-D MHD model of the heliosphere; the Sumerian god of winds and storms; EPIC: equatorial processes including coupling; EPP: energetic particle precipitation; EUV: extreme UV; FMT: flare monitoring telescope; GCR: galactic cosmic rays; GHG: greenhouse gas; GNSS: global navigation satellite system; GPS: global positioning system; HEPPA: high-energy particle precipitation in the atmosphere; HSS: high-speed stream; IAGA: International Association of Geomagnetism and Aeronomy; IAUS300: 300th Symposium of the International Astronomical Union/Union Astronomique Internationale; ICME: interplanetary CME; ICSU: International Council for Science; IGY: International Geophysical Year; IMAGE: Imager for Magnetopause-to-Aurora Global Exploration; IMS: International Magnetospheric Study; IPCC: Intergovernmental Panel on Climate Change; IPS: interplanetary scintillation; IQSY: International Quiet Sun Year; ISCCP: International Satellite Cloud Climatology Project; ISCS: International Solar Cycle Study; ISEST: International Study of Earth-affecting Solar Transients; ISSI: International Space Science Institute; ISTP: International Solar–Terrestrial Physics; IT system: ionosphere–thermosphere system; ITM: Ionosphere–thermosphere–magnetosphere; LISN: Low-Latitude Ionospheric Sensor Network;

LONET: LOngitudinal NETwork; MAP: Middle Atmosphere Program; MEE: medium energy electron; MESSENGER: Mercury Surface, Space Environment, Geochemistry, and Ranging; MHD: magneto-hydrodynamics; MLT: mesosphere–lower thermosphere; MST13: 13th Workshop on Technical and Scientific Aspects of MST Radar; NAOJ: National Astronomical Observatory of Japan; NASA: National Aeronautics and Space Administration; NCAR: National Center for Atmospheric Research; NLC: noctilucent cloud; PMC: polar mesospheric cloud; PSMOS: Planetary Scale Mesopause Observing System; REP: recurrent energy particle; ROSMIC: role of the Sun and the middle atmosphere/thermosphere/ionosphere in climate; SBUV: solar backscatter ultraviolet; SCOSTEP: Scientific Committee on Solar–Terrestrial Physics; SEE: Solar Evolution and Extrema; SEP: solar energetic particle; SMART: Solar Magnetic Activity Research Telescope; SMY: solar maximum year; SOHO: Solar and Heliospheric Observatory; SOLARIS: Solar Influences for SPARC; SPARC: stratospheric processes and their role in climate; SPeCIMEN: specification and prediction of the coupled inner-magnetospheric environment; S-RAMP: STEP—results, application, and modeling phase; SSI: solar spectral irradiance; SSN: sun spot number; STEP: Solar–Terrestrial Energy Program; STEREO: Solar TEerrestrial RElations Observatory; STP: solar–terrestrial physics; StratWarm: stratospheric warming; TEC: total electron content; TG: task group; TIMED: Thermosphere, Ionosphere, Mesosphere Energetics, and Dynamics; TIME-GCM: thermosphere–ionosphere–mesosphere–electrodynamics general circulation model; TOSCA: toward a more complete assessment of the impact of solar variability on the Earth's climate; TSI: total solar irradiance; UV: ultraviolet; VarSITI: Variability of the Sun and Its Terrestrial Impact; WACCM: whole atmosphere community climate model; WDS: World Data System; WIND: comprehensive solar wind laboratory for long-term solar wind measurements.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
TT proposed the topic and outlined the article. MS, NG, and TT collaborated on the construction of the manuscript. All authors read and approved the final manuscript.

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