Project for Solar–Terrestrial Climate Research

In 1801, British astronomer William Herschel discovered a significant correlation between the number of sunspots and market value of wheat in London (published by the Royal Society). He concluded that a reduction in the number of sunspots affected a change in climate, which altered wheat yields and influenced the price of wheat. This study was the first to examine the correlations between the Sun, climate, and society (human life). Even now, correctly identifying the characteristic variations in solar activity and investigating their effects on climate change and modern society remain important research topics in academia and society.

Very few sunspots were observed between March 7 and March 20, 2017. The cycle of solar magnetic activity corresponding to the sunspot cycle was estimated to be approximately 14 years during the Maunder Minimum. The sunspot cycle in solar cycle 24, which began in 2008, grew to approximately 13 years, similar to that during the Maunder Minimum. Therefore, we are entering a period of low solar activity and cooling on a global scale may occur in the near future. To offer a qualified opinion on the likelihood of this prediction, we must examine diverse viewpoints on how solar activity affects the climate. The globally averaged surface temperature showed a clear upward trend after the latter half of the 20th century. However, it continued to increase by 0.03–0.05 ℃ per 10 years from 1998 to 2012 and the global warming pause is called the “global warming hiatus.” Nonetheless, the atmospheric greenhouse gas concentration is increasing yearly; however, a clear rise is not observed in surface temperature observations. The topic “global warming hiatus” was taken up by Internet news and blogs, moved over the scientific community, and then had a considerable impact on the public. Based on a detailed analysis of the meteorological dataset from land and ocean temperatures and computer experiments with climate models, it was suggested that the global warming hiatus was caused by natural characteristics. Although we still cannot provide a sufficient explanation, decadal-centurial-time scale climate change is indirectly driven by secular variations in solar activity. Encouraging an understanding of the characteristics and mechanisms of short-term natural fluctuations appearing in the age of global warming will predict anthropogenic climate change more reliably. It is extremely important to develop environmental policies that influence human society.

Radiocarbon (^{14}C) and Beryllium-10 (^{10}Be), known as cosmogenic isotopes, are produced at a rate that varies based on the intensity of incoming cosmic rays (CRs) to Earth, which are in turn influenced by solar activity. Analyzing ^{14}C in tree rings and ^{10}Be in polar ice cores is an effective approach for studying the long-term variations in solar activity that go back tens of thousands of years. Analyses of ^{14}C and ^{10}Be suggested that episodes of declining solar activity resembling the Maunder Minimum have occurred 12 times throughout the Holocene, which spans the past ten thousand years. Comparing cosmogenic isotopes with paleoclimate data can improve the understanding of solar-driven climate change over a long timescale. We have accumulated evidence that will be effective for studying the mechanisms by which variations in solar activity affect climate and human society. The interdisciplinary project for Solar-Terrestrial Climate Research at the ISEE integrates the latest knowledge in solar physics, meteorology, climatology, environmental studies, paleoclimatology, space physics, and CR physics to better understand the variability in solar activity, foster an understanding of solar-driven Earth systems, and contribute to predicting future global environments.

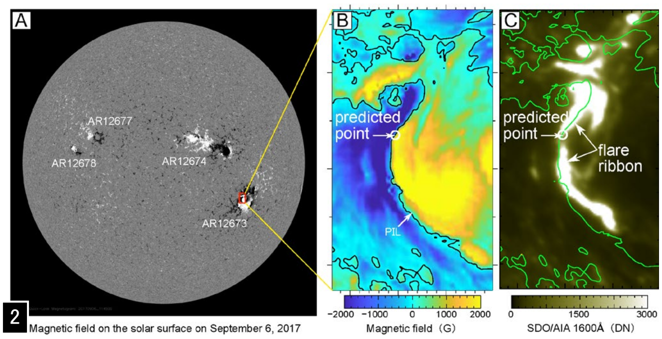
Main Activities

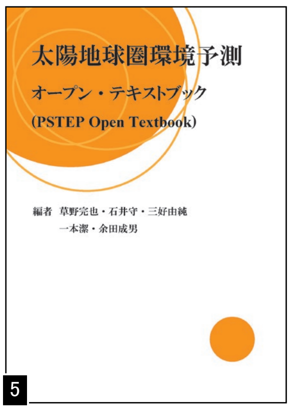
The ISEE operates a Tandetron ^{14}C AMS measurement system to trace the details of past ^{14}C changes caused by solar changes. To investigate the details of past solar changes and solar events, such as solar high-energy proton events (SPE), the accuracy and efficiency of AMS ^{14}C measurements have been improved. Some of our data obtained at the ISEE were used to develop an internationally used radiocarbon age calibration dataset (IntCal20) showing past ^{14}C changes in the atmosphere. On the other hand, we performed the accumulation of high temporal resolution paleoclimate datasets with the promotion of the International Continental Scientific Drilling Program (ICDP), Deep Sea Drilling Program, and the Suigetsu Varve Sediment Project. These efforts significantly contributed to the construction of the platform to promote “Solar-Terrestrial Climate Research” with researchers in solar physics, meteorology/climatology, environment, paleoclimatology, Earth magnetism, and cosmic ray physics.

Project for Space–Earth Environmental Prediction

The solar activity and dynamics of the space environment can significantly impact human socio-economic systems and the global environment. For example, the giant solar flare observed by the British astronomer Richard Carrington in 1859 caused powerful magnetic storms, called the Carrington event. If such an event occurred in the modern era, power grids, satellites, aviation, and communication networks could be damaged globally. Moreover, analyses of the latest stellar observations and cosmogenic isotopes in tree rings suggest even larger solar flares. However, the onset mechanisms of solar flares and their subsequent processes have not yet been fully explained. Thus, modern society is at risk of severe space weather disturbances caused by such solar explosions, and understanding and predicting variations in the space–Earth environment is an important scientific subject and a crucial issue for modern society.

The Project for the Space-Earth Environmental Prediction was promoted during the third medium-term target period for the purpose to advance of synergistic development for predictive technology as scientific research and a social infrastructure via cooperation and interaction with experts in solar physics, geomagnetism, space sciences, meteorology/climatology, space engineering, and related fields. This project produced excellent research results shown in the figure below, based on ISEE Joint Usage/Research Programs and the support of a Grant-in-Aid for Scientific Research on Innovative Areas from MEXT.





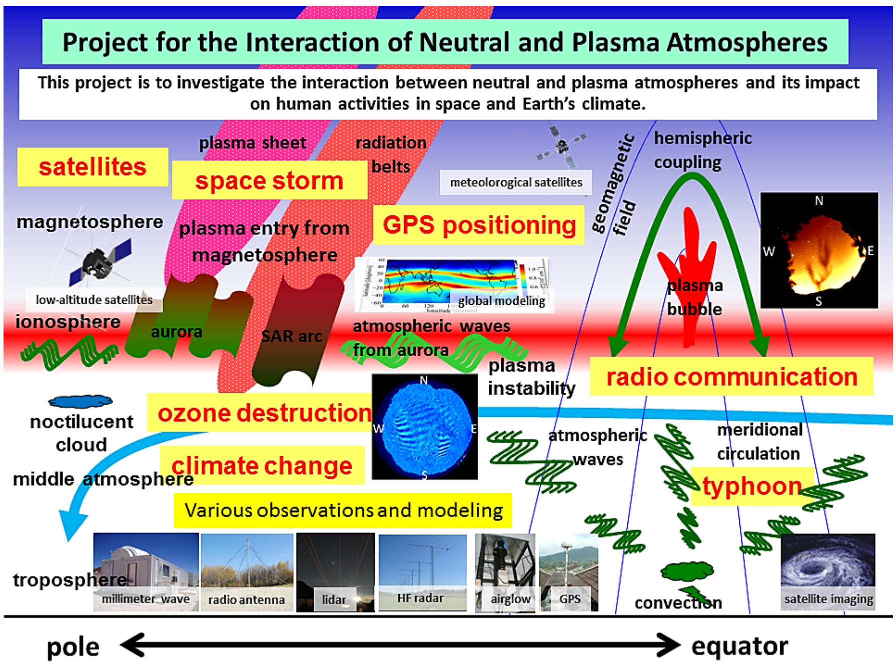
1: The 2nd ISEE Symposium "PSTEP-4: Toward the Solar-Terrestrial Environmental Prediction as Science and Social Infrastructure", Jan. 2020, Nagoya University (http://www.pstep.jp/news/20200127.html) 2: Succeeded in developing the first physics-based model that can accurately predict imminent large solar flares (Kusano et al., 2020, Science, doi:10.1126/science.aaz2511) 3: ISEE/PSTEP International Workshop on the Solar Cycle 25 Prediction, Nov, 2017 4: PSTEP Summer School 2017 in Rikubetsu (https://www.isee.nagoya-u.ac.jp/pstep/news/20170704ss.html) 5: PSTEP Open Textbook (https://nagoya.repo.nii.ac.jp/records/2001522) 6: ISEE/PSTEP International Workshop on the Benchmarks for Operational Solar Flare Forecasts, Oct. 2017 7: Science Meeting on Modeling Study for Solar- Terrestrial Environment Prediction (2017–2021)

Project for the Interaction of Neutral and Plasma Atmospheres

The ionosphere is part of the Earth's upper atmosphere and is partly ionized by solar ultraviolet emissions. The peak altitudes of plasma density in the ionosphere are 300–400 km, where most low-altitude space vehicles fly. Thus, ionospheric plasma significantly affects human activities in space, such as radio communications and positioning by Global Navigation Satellite System (GNSS). The consequences of climate change are significant in the upper atmosphere and ionosphere. As shown in the figure below, neutral–plasma interaction processes in the upper atmosphere and ionosphere can be observed as various phenomena occurring from high to low latitudes. The aurora in the polar regions is caused by the precipitation of high-energy plasma, which heats the upper atmosphere and generates atmospheric waves and disturbances that propagate toward low latitudes. However, ionospheric plasma instabilities, known as plasma bubbles, occur in the equatorial upper atmosphere, interfering with satellite–ground communication and GNSS positioning. These phenomena can be measured using various ground-based remote-sensing instruments, such as airglow imagers, magnetometers, radars, lidars, and millimeter-wave telescopes. This interdisciplinary project has investigated the interactions between the neutral and plasma components of the Earth's atmosphere, using various ground remote-sensing techniques and *in-situ* satellite measurements, and global and regional high-resolution modeling of neutral–plasma interactions. This project has contributed to the reliable use of space by humans and our understanding of possible plasma effects on Earth's climate change. From FY2016–2021, we conducted 69 international collaborative studies, 57 domestic collaborative projects, and 120 domestic meetings for the ISEE, as shown in the table. Various scientific results have been obtained through these collaborative projects.

	2016	2017	2018	2019	2020	2021	total
international collaborative projects	11	12	11	9	14	12	**69**
domestic collaborative projects	8	8	8	9	13	11	**57**
domestic meetings	18	22	21	20	22	17	**120**
total	**37**	**42**	**40**	**38**	**49**	**40**	**246**

The number of collaborative research projects related to the Project for the Interaction of Neutral and Plasma Atmospheres.



Research topics of the project for the interaction of neutral and plasma atmospheres.

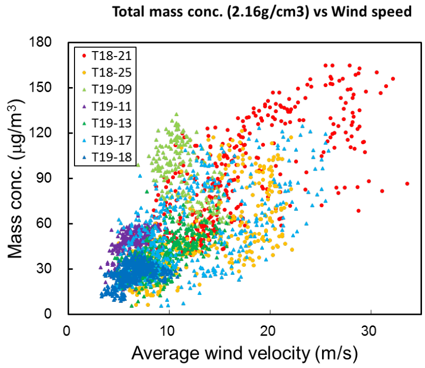
Project for Aerosol and Cloud Formation

Hydrometeors and aerosols interact closely in their generation and dissipation, and play important roles in atmospheric water circulation, the formation of convective clouds and typhoons, and the Earth's radiation budget. However, hydrometeors and cloud-precipitation systems have been studied at the Hydrospheric Atmospheric Research Center, and aerosols and related processes have been studied at the Solar-Terrestrial Environmental Laboratory. In a joint research program, researchers from both centers cooperated to study the interaction between aerosols and hydrometeors, and their variations in the formation of precipitation by field observations and numerical simulations.

Observational studies of hydrometeors and aerosols

Drone observation of sea spray particles: Sea sprays are sources of water vapor and aerosols in the atmosphere. They may influence development of convective clouds. We attempted drone observation of sea spray particles in August 2016 on Tarama Island, Okinawa. The cloud particle sonde was lifted by a drone 2 m above the sea level, and sea spray particles were observed. Although observations were made under weak wind conditions, sea spray particles were successfully observed.

Cloud and aerosol observations in the United Arab Emirates (UAE): Using an aircraft equipped with an aerosol-cloud-precipitation observation system, aerosol observations were conducted over the UAE to clarify the physical and chemical characteristics of aerosols. The effects of aerosols on clouds and precipitation were studied using the observed data. These data were also used to verify the aerosol activation process in the numerical model.



Relation of mass concentration of aerosol particles with diameters between 0.3 and 10 μm and wind speed during the passage of seven typhoons.

Observations of aerosol particles in Okinawa: Aerosol observations were conducted at the University of Ryukyus. We measured the size distribution of aerosol particles in the summer and autumn of 2018 and 2019 using an optical particle analyzer. For seven typhoons that passed near the site, the effect of wind speed on the mass concentration of aerosol particles with diameters between 0.3 and 10 μm was analyzed. The mass concentration was found to increase by 50 $\mu g/m^3$ as the wind speed increased by 10 m/s (Fig.). In addition, to study the concentrations of sea salt and dissolved organic carbon (DOC) in the aerosols, we collected bulk aerosols continuously since Sep. 2018, even during typhoons. The amount of sea salt in the aerosols showed a good positive correlation with wind speed. The DOC concentrations in aerosols collected under different wind speed conditions in this study and the fraction of sea salt in the aerosols suggest that oceanic DOC in actual atmospheric aerosols is approximately 700 times more concentrated.

Numerical studies of hydrometeors and aerosols

Super-Droplet Method with CReSS and impact experiments of aerosols on warm rain: The Super-Droplet Method (SDM) developed by Professor Shima of the University of Hyogo was coupled with the CReSS model and aerosol impact experiments were performed for warm rain. A significant difference was found in cloud and precipitation amounts according to the amount of aerosols. The maximum rainfall intensity exceeded 80 mm h^{-1} at a low aerosol density.

Numerical modeling of aerosol-cloud interaction: We developed CReSS-4ICE-AEROSOL, which implements aerosol-cloud-precipitation integrated microphysics parameterization with various aerosols in the atmosphere and hydrometeors as prognostic variables. Idealized experiments on cumulonimbus clouds with strong updrafts were conducted to investigate the effect of the amount of anthropogenic aerosols on the microphysical structure of the cloud. It has been shown that increasing anthropogenic aerosols by an order of magnitude increases the concentration and mixing ratio of cloud ice in the anvil associated with the cumulonimbus cloud several times. Furthermore, by providing aerosol information from the global aerosol model SPRINTARS as initial and boundary values, the actual cloud and aerosol processes can be simulated.