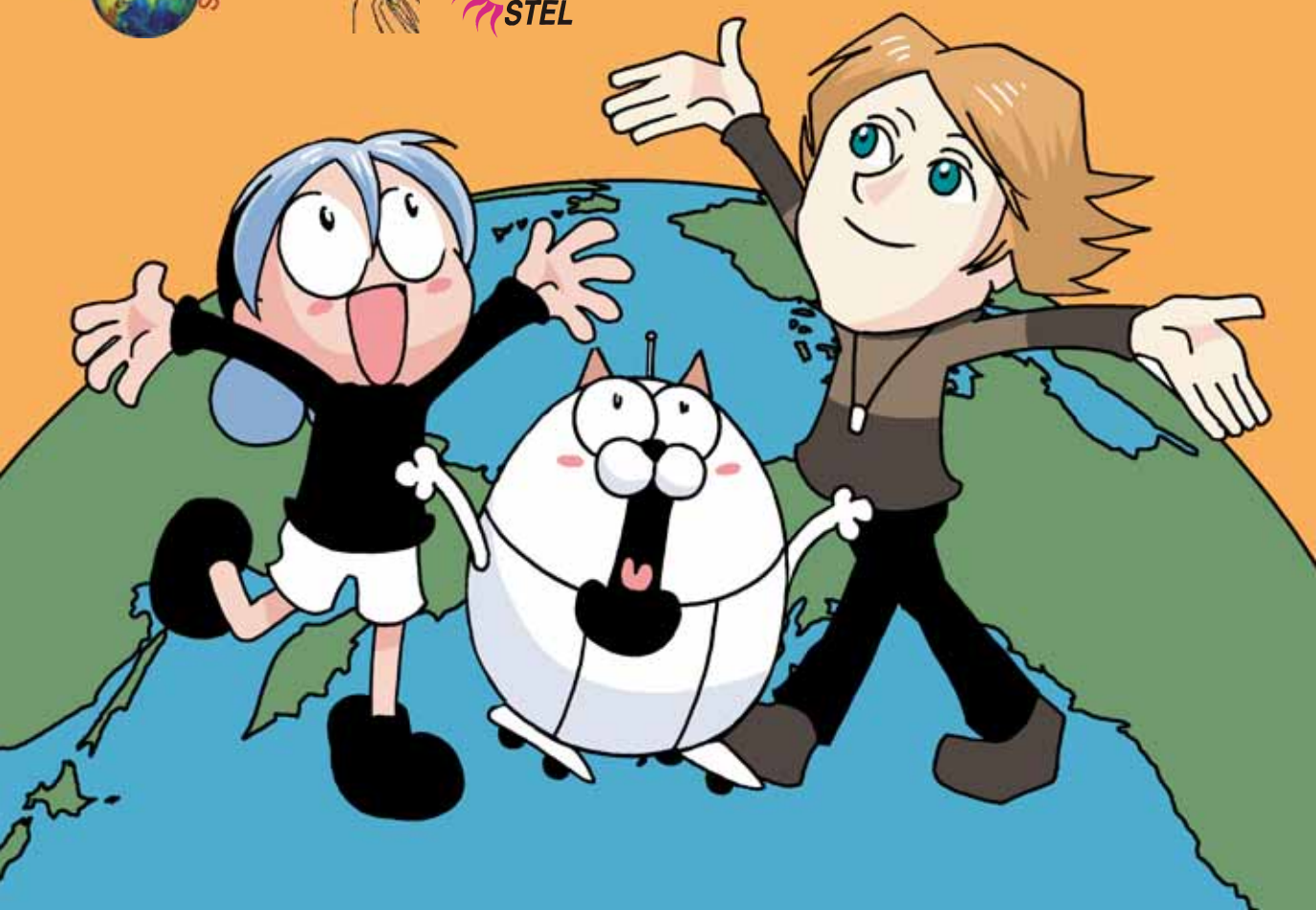
What is the Sun–Climate Relationship?

By **Hayanon**
Translated by Y. Noda and Y. Kamide
Supervised by Judith Lean

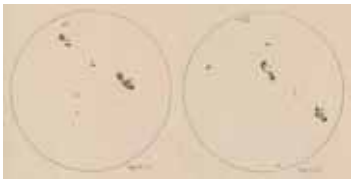


Centuries of Scientific Inquiry

GALILEO GALILEI (1564-1642)

When I pointed my telescope at the Sun, I saw...dark blotches. It was in 1610. They have a common movement and are mostly of an irregular figure... Indeed they are in the body of the Sun itself, which revolves in its place and carries them with it. The teachings of Aristotle, with which my own Catholic Church agrees, tell me that all celestial objects are incorruptible. Yet the Sun, this most magnificent of all celestial objects, is blemished.

It would be almost two hundred years before Schwabe reported, in 1854, that Galileo's sunspots regularly appear and disappear on the Sun's surface, in a cycle of about 11 years.



Sketch of sunspots on June 23 (left) and 25 (right), 1613.

SAMUEL PIERPONT LANGLEY (1834-1906)

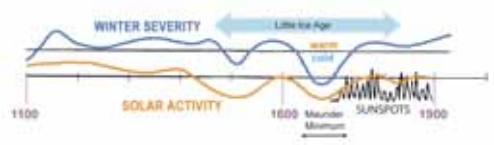
Sunspots come and go in cycles. I wondered …might such earthly things as famine in India and grain prices in London be connected to the Sun? Yet how could changes in the number of sunspots affect climate? The most direct influence would come if the change meant a rise or fall in the total energy the Sun radiated upon the Earth, the so-called "solar constant." To measure the solar constant of radiation I invented an extremely sensitive and accurate instrument. It measures radiant energy by correlating the radiation-induced change in electrical resistance of a blackened metal foil with the amount of radiation absorbed. I used it to observe the amount of heat the Sun sends the Earth. Since we are the children of the Sun, I am convinced that it is a worthy problem to learn how things earthly depend upon this ruler of our days.

It would be another 100 years before instruments based on Langley's idea were launched on Earth-orbiting satellites, where, free of interference by the Earth's atmosphere, they began recording what were indeed real variations in the so-called solar "constant."

Langley's bolometer to measure the solar constant.

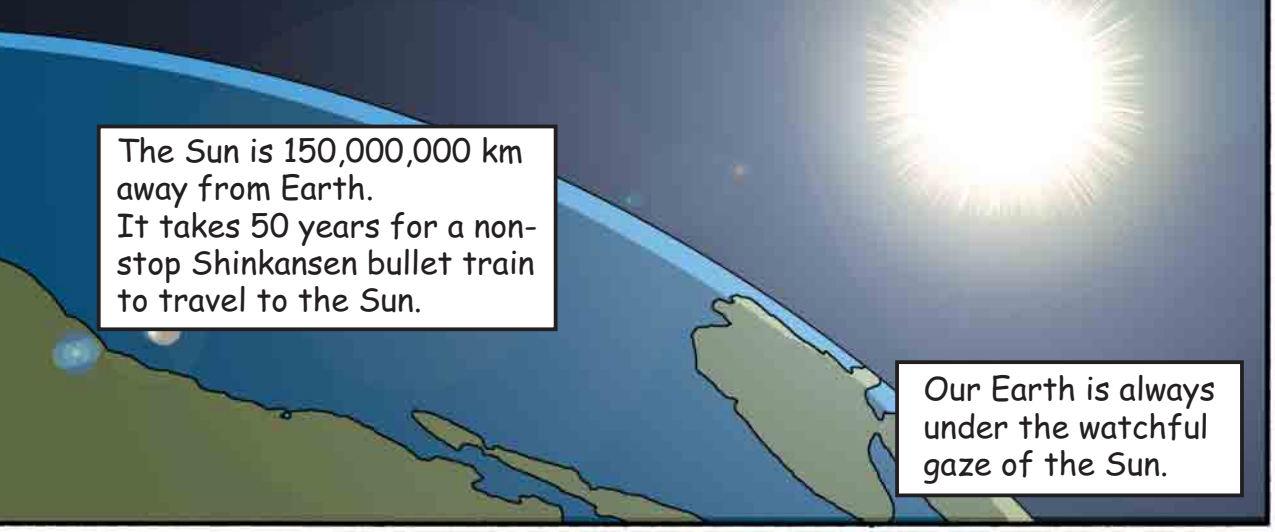
JOHN A. EDDY (1931-)

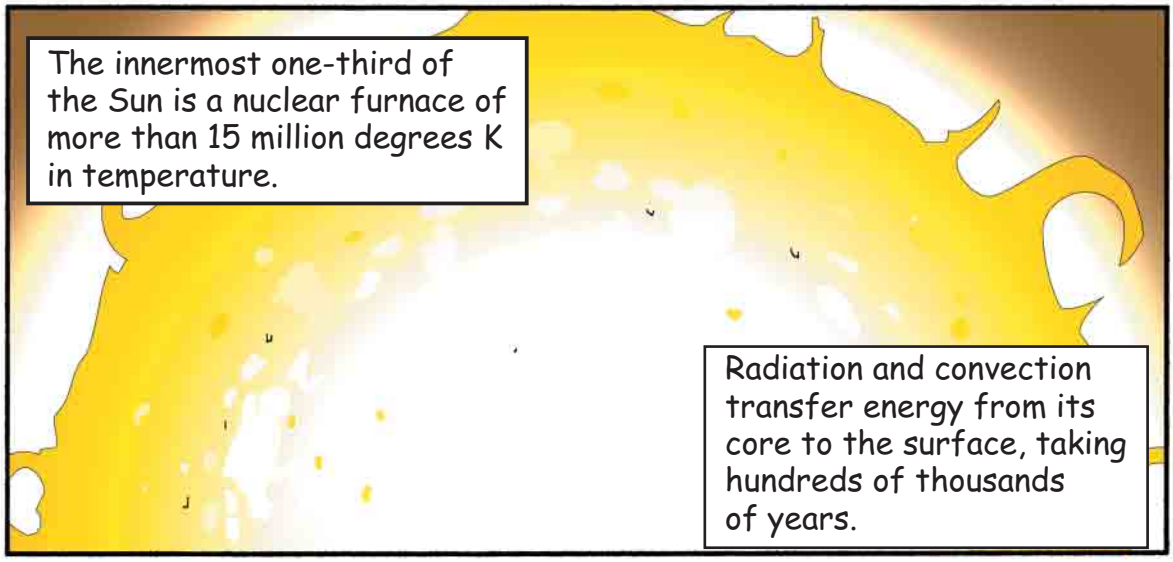
I had been taught that the Sun was indeed variable, but regularly so… But I started investigating historical records of auroras, naked eye sunspots, eclipse drawings of the Sun's outer atmosphere and carbon-14 in tree-rings. During the 16th-17th centuries, sky-watchers had observed almost no sunspot activity... I looked at paintings, among other stuff, from the 17th century, and became more and more convinced that there was a likely long-term connection between the irregular variations in solar activity and major climate shifts – such as the severity of winter in London and Paris. At first, I started to make this result go away, mostly because of a prejudice about Sun-climate relationships, and what I thought was true about the Sun. But the original drawings of the Sun that I had come across in rare books were so precise and excellent they convinced me that the historical reports were to be trusted.



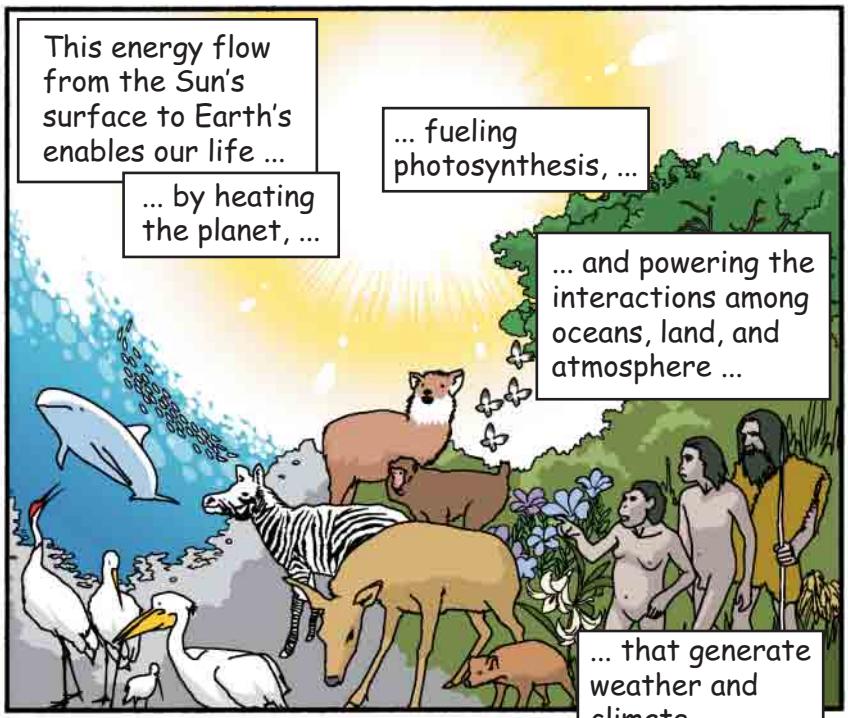
Winter severity and solar activity over the last 1000 years.

It would be a few more decades before scientists, grudgingly at first, began to consider the Sun's variations in activity as a credible cause of climate change. This occurred only after sufficiently long databases were collected from space of both the Sun and the Earth, to properly characterize and understand the variations in the Sun's brightness, and to relate them to temperatures of the Earth's surface and atmosphere.


The Sun is 150,000,000 km away from Earth.
It takes 50 years for a non-stop Shinkansen bullet train to travel to the Sun.
Our Earth is always under the watchful gaze of the Sun.


The innermost one-third of the Sun is a nuclear furnace of more than 15 million degrees K in temperature.
Radiation and convection transfer energy from its core to the surface, taking hundreds of thousands of years.


The solar light reaches Earth in just 8 minutes.


This energy flow from the Sun's surface to Earth's enables our life ...
... by heating the planet, ...
... fueling photosynthesis, ...
... and powering the interactions among oceans, land, and atmosphere ...
... that generate weather and climate.

What are the practical consequences for the Earth of the Sun's watchful gaze?

Thomas Edison, called the Father of Modern Invention, conceived the idea of "a great research laboratory" which led to the creation of NRL in 1923. NRL is a campus-like complex of diverse scientific facilities, with a staff of more than 2,500 researchers, engineers, technicians and support personnel.

Naval Research Laboratory (NRL) in Washington, D.C.

Let's learn together how the Earth's climate works, influenced by the Sun.

Good deal!

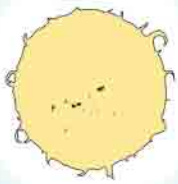
NRL scientist Dr. Judith Lean

Science lover Mol

Her robotic dog Mirubo

The Sun-Earth system seems to have been sufficiently stable to have some sort of life for a few billion years, but extensive observations of the Sun made in the past decades, ...

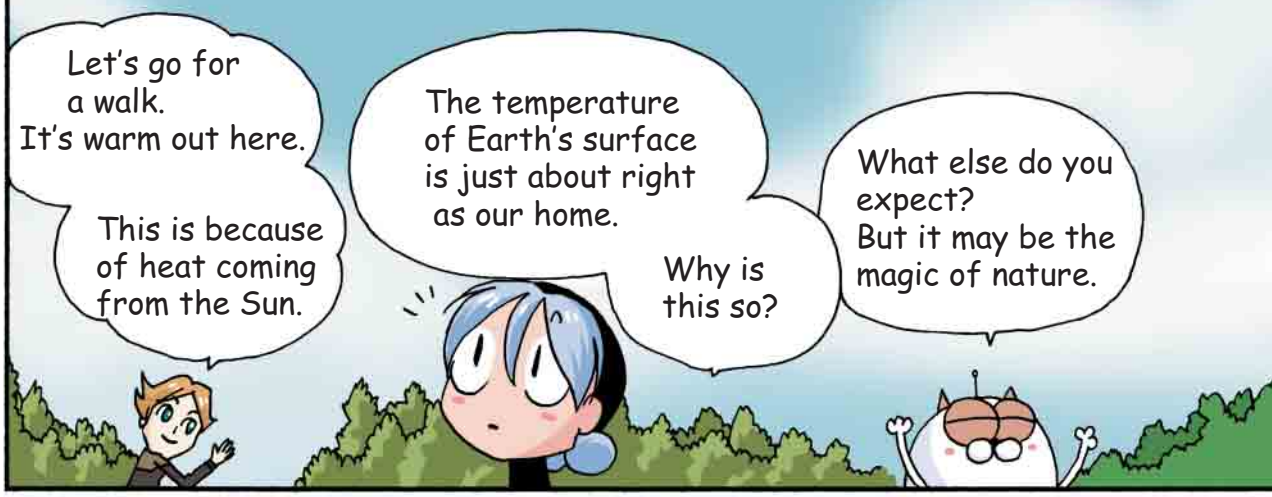
... primarily from space, reveal that the Sun's energy output is changing all the time.

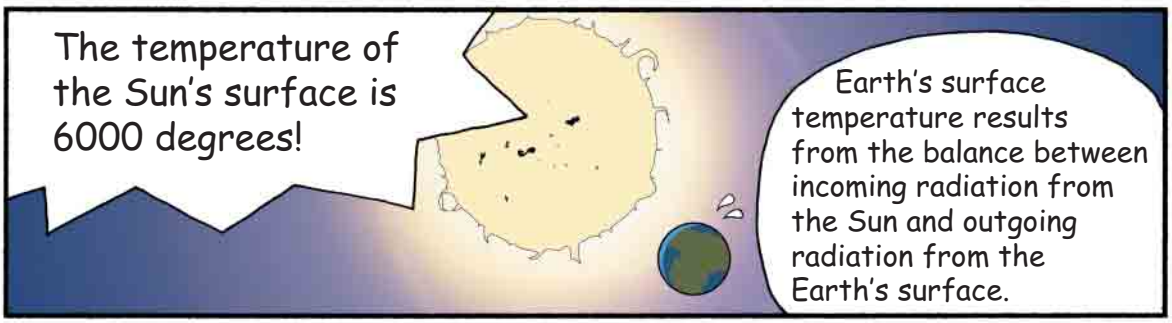


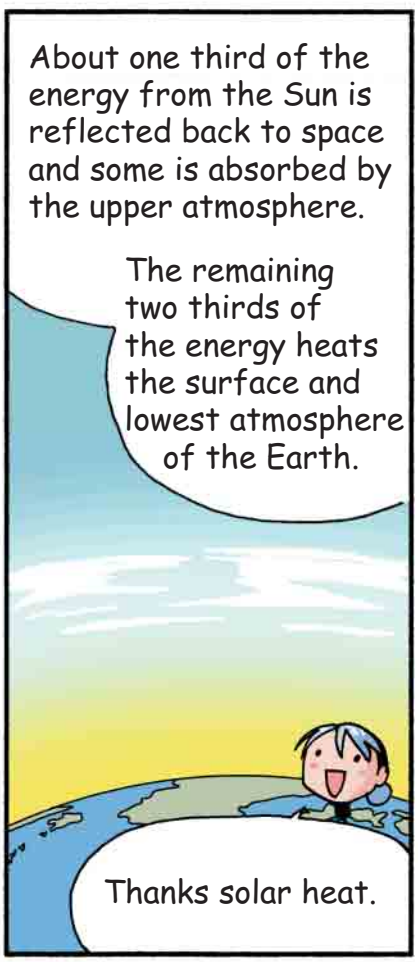
For more than a century, people reported correlations of sunspots with grain prices or famine.

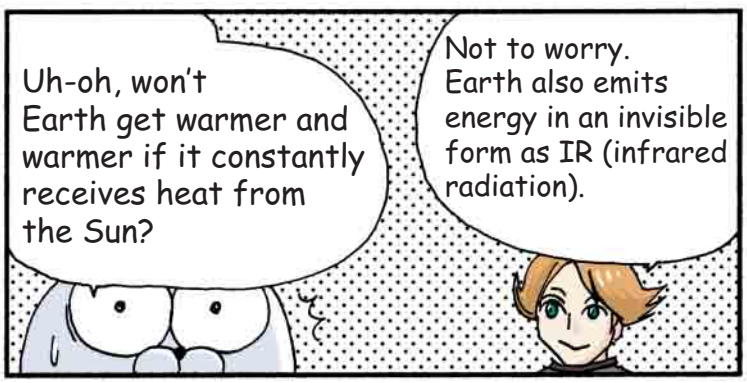
However, those findings have been dismissed as coincidences ... until recently.

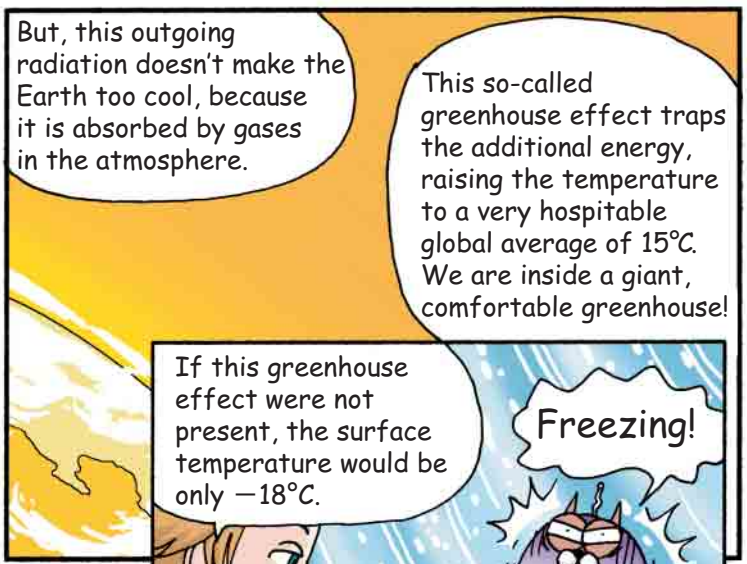
Sun-climate connections are apparent in many new datasets.


Let's go for a walk. It's warm out here.
This is because of heat coming from the Sun.
The temperature of Earth's surface is just about right as our home.
Why is this so?
What else do you expect? But it may be the magic of nature.


The temperature of the Sun's surface is 6000 degrees!
Earth's surface temperature results from the balance between incoming radiation from the Sun and outgoing radiation from the Earth's surface.


About one third of the energy from the Sun is reflected back to space and some is absorbed by the upper atmosphere.
The remaining two thirds of the energy heats the surface and lowest atmosphere of the Earth.
Thanks solar heat.


Uh-oh, won't Earth get warmer and warmer if it constantly receives heat from the Sun?
Not to worry. Earth also emits energy in an invisible form as IR (infrared radiation).


But, this outgoing radiation doesn't make the Earth too cool, because it is absorbed by gases in the atmosphere.
This so-called greenhouse effect traps the additional energy, raising the temperature to a very hospitable global average of 15°C. We are inside a giant, comfortable greenhouse!
If this greenhouse effect were not present, the surface temperature would be only −18°C.
Freezing!

Let's look into more details about the effect of the solar energy on the Earth.

Some light from the Sun is invisible to human eyes.
I guess you have heard of UV (ultraviolet) and IR?

Yah.

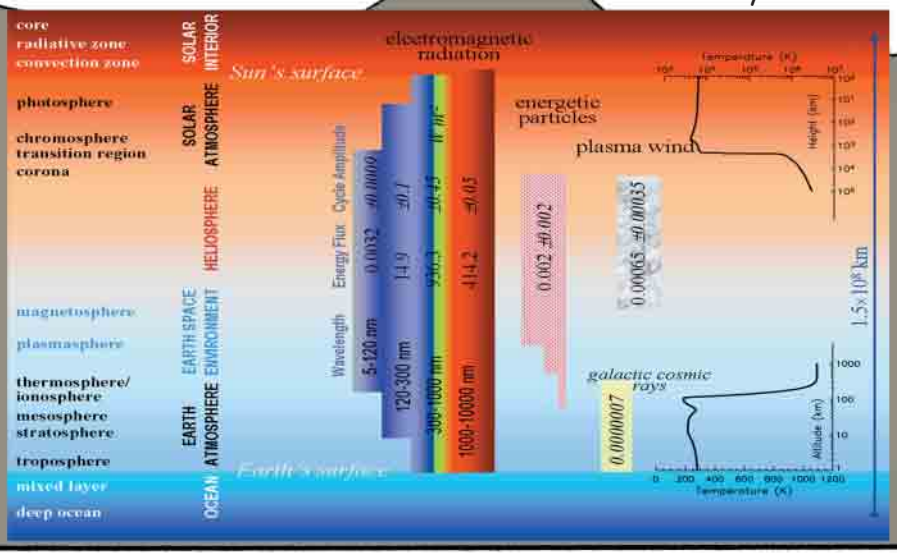
UV, I know that …

… but what is it?

Is that something to eat?

Among various types of light from the Sun, UV is most important for heating the Earth's atmosphere. Increasingly higher layers of the Sun's atmosphere emit UV light that varies increasingly more than visible light. This UV light is absorbed at increasingly higher altitudes above the Earth's surface, and causes increasingly larger variations in the atmosphere.

Light emitted from the Sun's outer atmosphere is absorbed in the Earth's outer atmosphere, creating within it the ionosphere, layers of ionized gases. Light emitted from the Sun's lower atmosphere is absorbed in the Earth's middle atmosphere, where it creates the ozone layer.

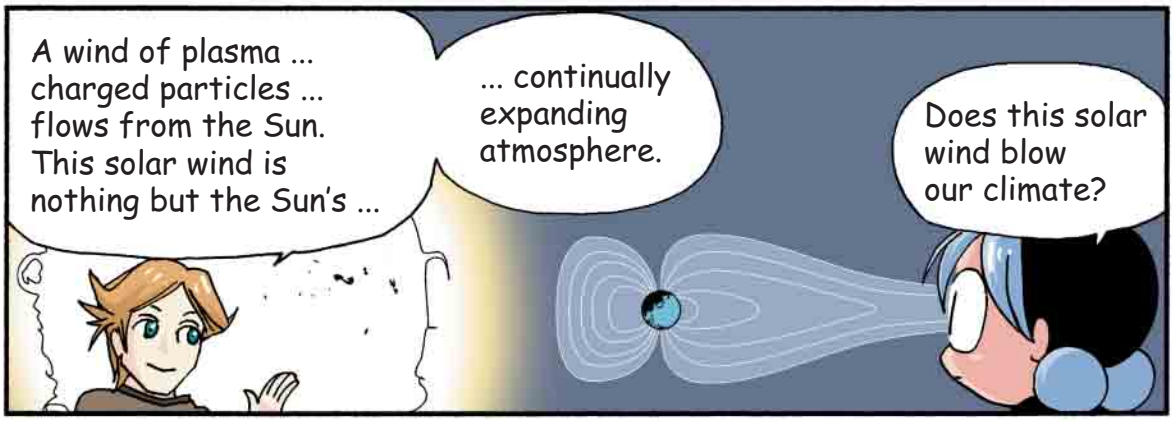


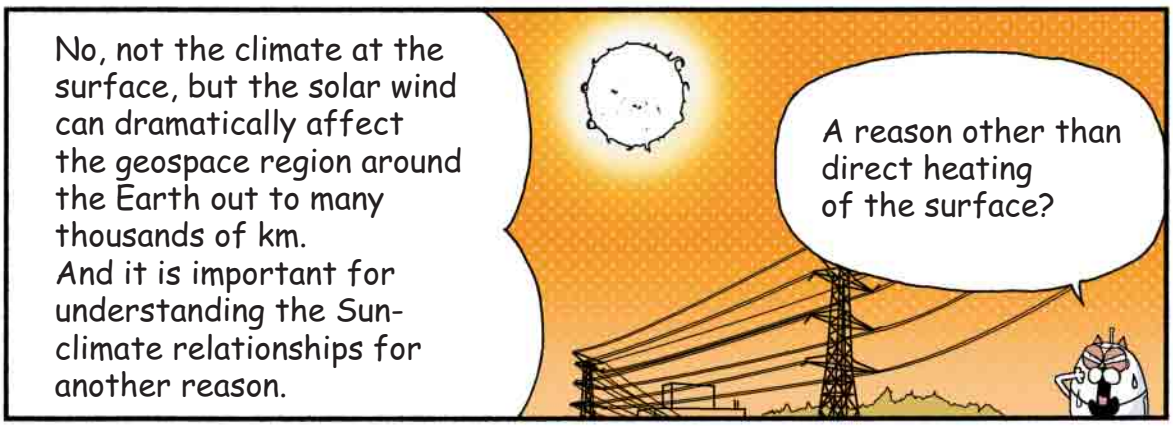
Ozone's absorption of solar UV light heats the atmosphere there,…

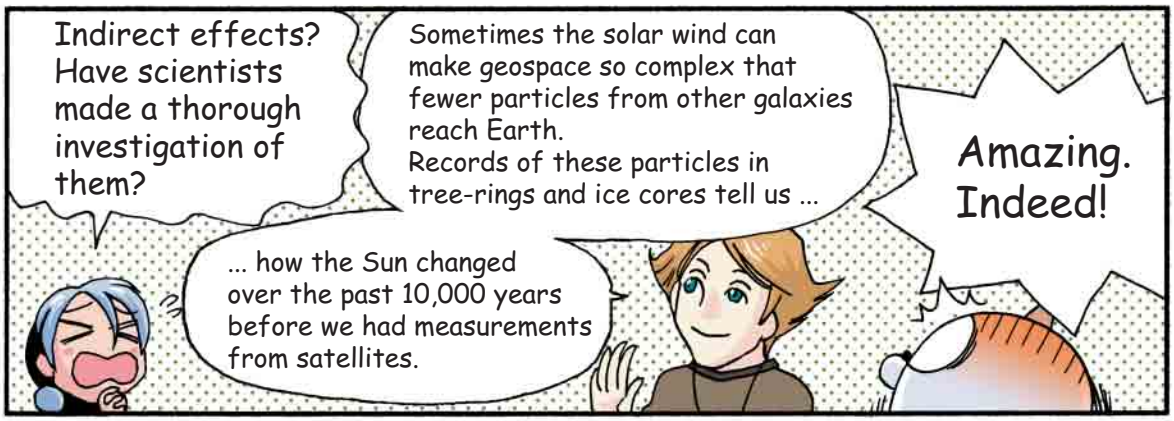
… making it warmer, and reversing its cooling trend with altitude away from the surface.

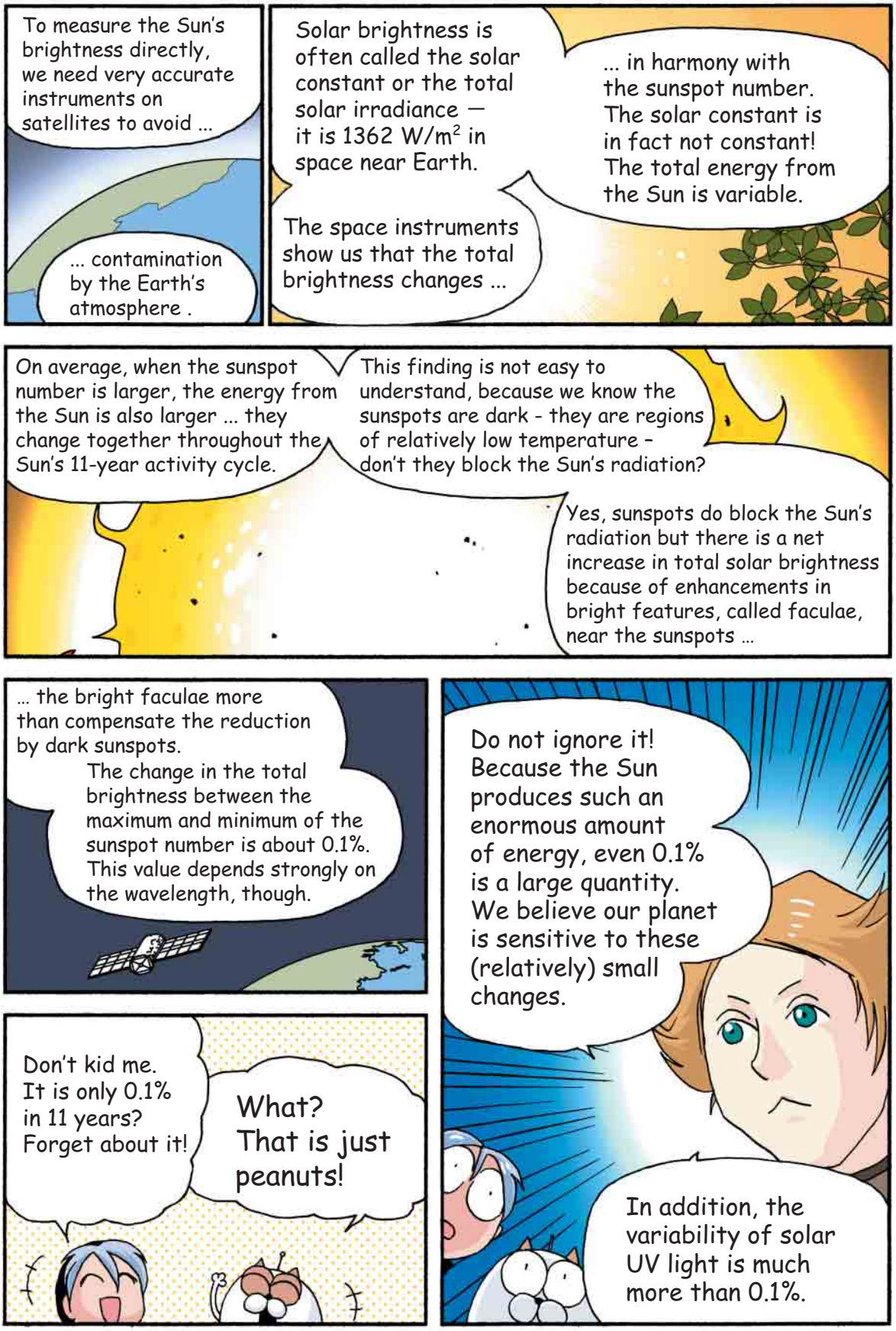
The ozone layer protects us from UV radiation that can damage cells in plants and animals and in us.

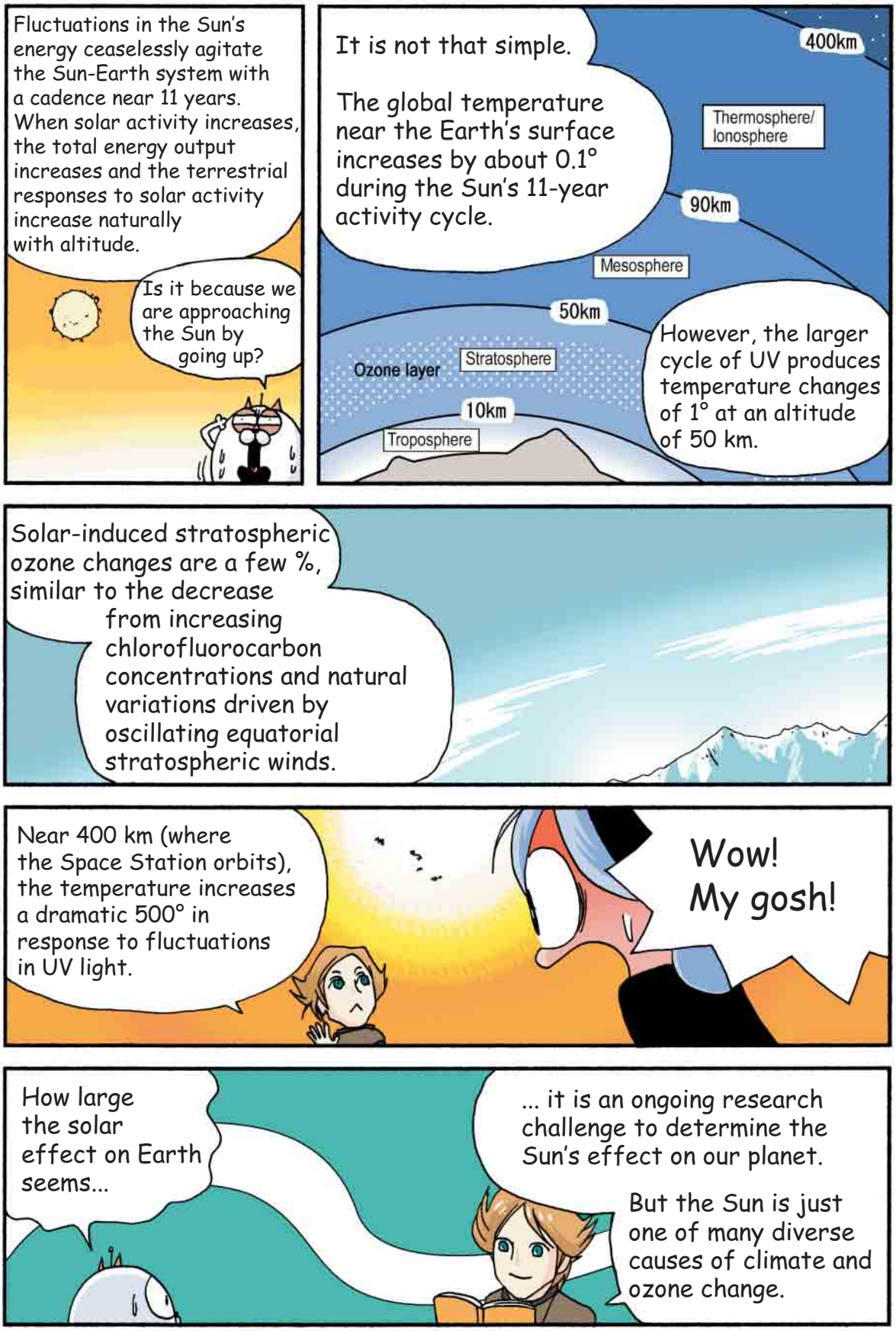

You may think that space between the Sun and Earth is empty, but charged particles and magnetic fields are there.
This is the heliosphere!


A wind of plasma ... charged particles ... flows from the Sun. This solar wind is nothing but the Sun's ...
... continually expanding atmosphere.
Does this solar wind blow our climate?


No, not the climate at the surface, but the solar wind can dramatically affect the geospace region around the Earth out to many thousands of km.
And it is important for understanding the Sun-climate relationships for another reason.
A reason other than direct heating of the surface?


Indirect effects? Have scientists made a thorough investigation of them?
Sometimes the solar wind can make geospace so complex that fewer particles from other galaxies reach Earth.
Records of these particles in tree-rings and ice cores tell us ...
... how the Sun changed over the past 10,000 years before we had measurements from satellites.
Amazing. Indeed!


To measure the Sun's brightness directly, we need very accurate instruments on satellites to avoid ...
... contamination by the Earth's atmosphere .
Solar brightness is often called the solar constant or the total solar irradiance — it is 1362 W/m^2 in space near Earth.
The space instruments show us that the total brightness changes ...
... in harmony with the sunspot number. The solar constant is in fact not constant! The total energy from the Sun is variable.
On average, when the sunspot number is larger, the energy from the Sun is also larger ... they change together throughout the Sun's 11-year activity cycle.
This finding is not easy to understand, because we know the sunspots are dark - they are regions of relatively low temperature – don't they block the Sun's radiation?
Yes, sunspots do block the Sun's radiation but there is a net increase in total solar brightness because of enhancements in bright features, called faculae, near the sunspots ...
... the bright faculae more than compensate the reduction by dark sunspots.
The change in the total brightness between the maximum and minimum of the sunspot number is about 0.1%. This value depends strongly on the wavelength, though.
Don't kid me. It is only 0.1% in 11 years? Forget about it!
What? That is just peanuts!
Do not ignore it! Because the Sun produces such an enormous amount of energy, even 0.1% is a large quantity. We believe our planet is sensitive to these (relatively) small changes.
In addition, the variability of solar UV light is much more than 0.1%.


Fluctuations in the Sun's energy ceaselessly agitate the Sun-Earth system with a cadence near 11 years. When solar activity increases, the total energy output increases and the terrestrial responses to solar activity increase naturally with altitude.
Is it because we are approaching the Sun by going up?
It is not that simple.
The global temperature near the Earth's surface increases by about 0.1° during the Sun's 11-year activity cycle.
400km
Thermosphere/ Ionosphere
90km
Mesosphere
50km
Stratosphere
Ozone layer
10km
Troposphere
However, the larger cycle of UV produces temperature changes of 1° at an altitude of 50 km.
Solar-induced stratospheric ozone changes are a few %, similar to the decrease from increasing chlorofluorocarbon concentrations and natural variations driven by oscillating equatorial stratospheric winds.
Near 400 km (where the Space Station orbits), the temperature increases a dramatic 500° in response to fluctuations in UV light.
Wow! My gosh!
How large the solar effect on Earth seems...
... it is an ongoing research challenge to determine the Sun's effect on our planet.
But the Sun is just one of many diverse causes of climate and ozone change.

You mean research by computer simulations?

Yes. Many model simulations have been made, and more are proposed.
But, observations and simulations differ markedly in different altitude regions ... this tells that we don't yet understand the Sun-Earth system properly.

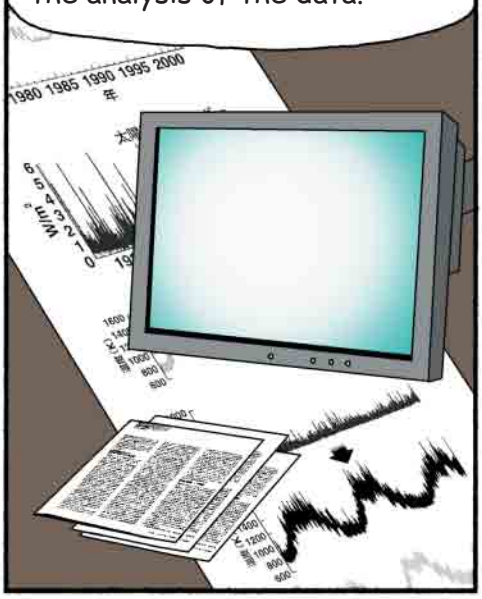
Whoa?

How come?

Surface temperature
Cloud cover
Drought
Rainfall
Tropical cyclones
Forest fire

Although these sometimes show a correlation with solar activity, models can only roughly reproduce their responses to solar variability.

For example, the modelled surface temperature changes at Earth in response to the 11-year cycle are much smaller than changes indicated by the analysis of the data.



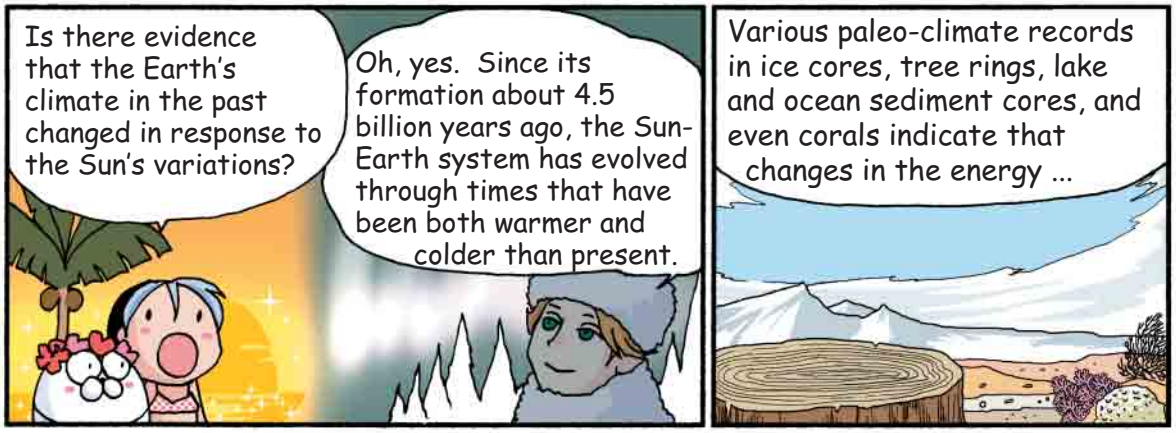
They also have different geographical responses.

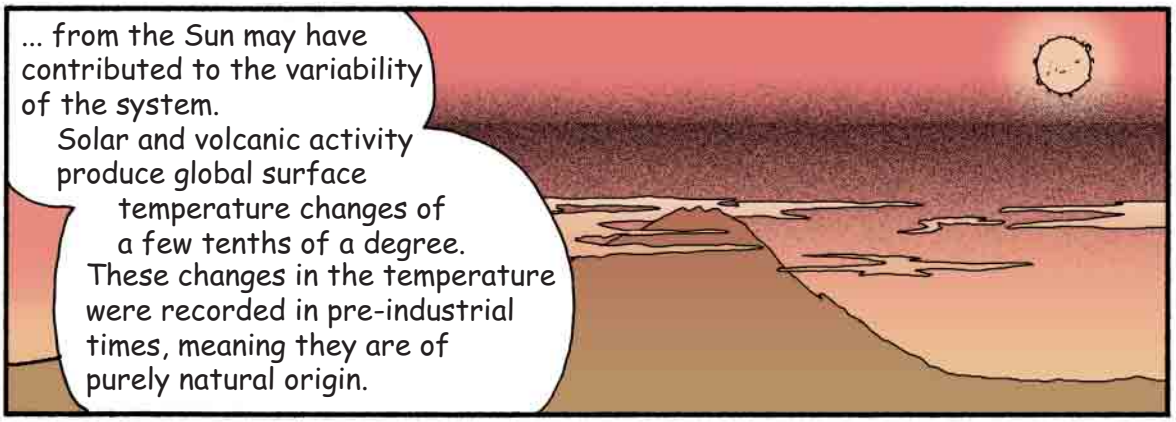
This is where we do not see good agreement.
Why do computer simulations provide only small values?

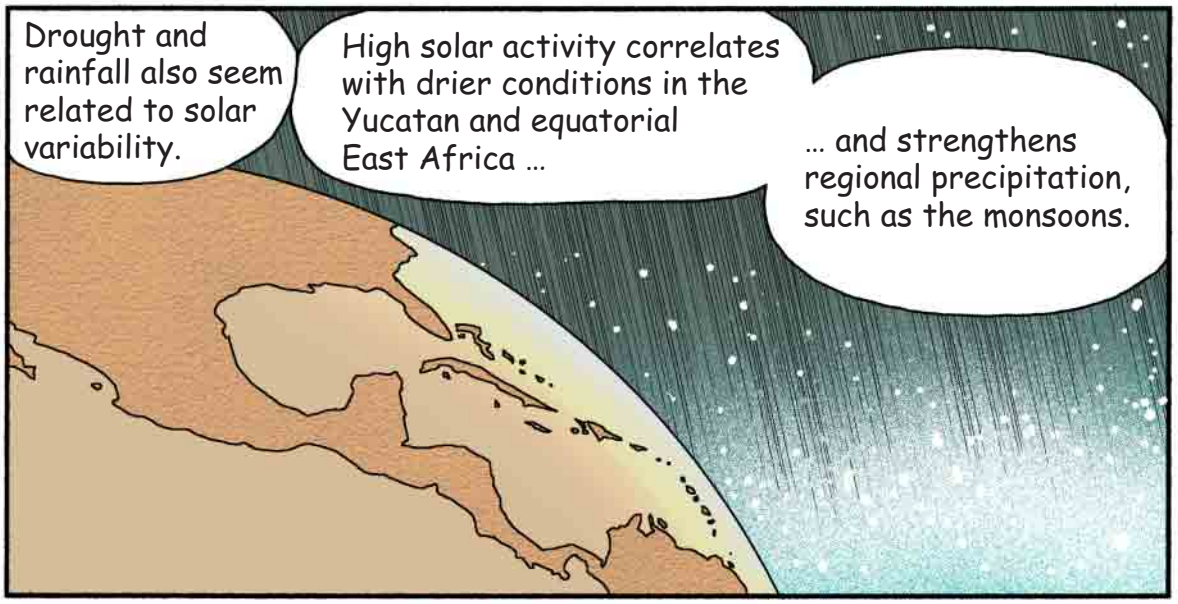
Either the empirical data give changes that are too large, or the models are not completely appropriate.

For example, some models don't simulate the ozone layer and the UV effects very well.

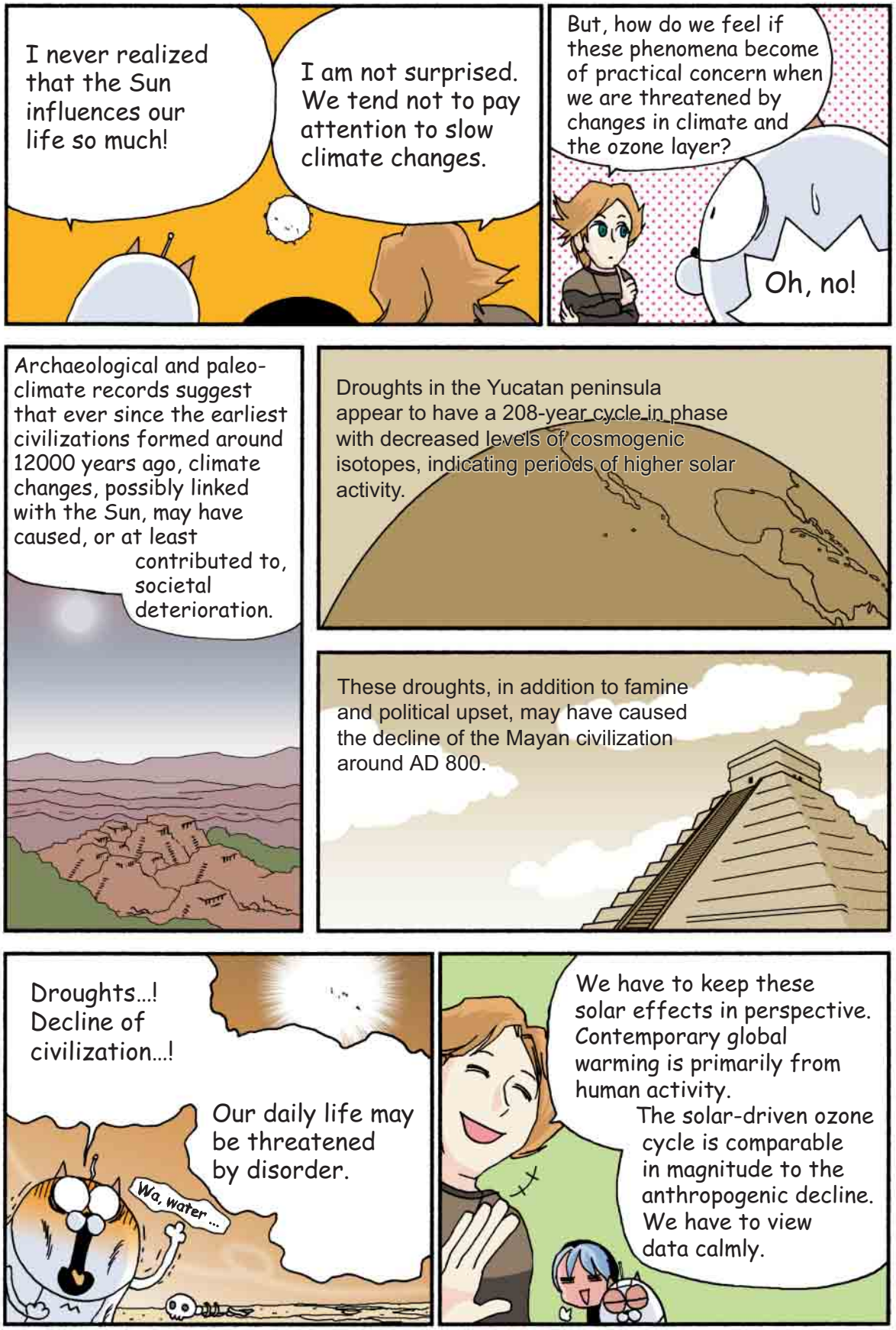
It appears that there are many points to be examined carefully.


Is there evidence that the Earth's climate in the past changed in response to the Sun's variations?
Oh, yes. Since its formation about 4.5 billion years ago, the Sun-Earth system has evolved through times that have been both warmer and colder than present.
Various paleo-climate records in ice cores, tree rings, lake and ocean sediment cores, and even corals indicate that changes in the energy ...


... from the Sun may have contributed to the variability of the system.
Solar and volcanic activity produce global surface temperature changes of a few tenths of a degree.
These changes in the temperature were recorded in pre-industrial times, meaning they are of purely natural origin.


Drought and rainfall also seem related to solar variability.
High solar activity correlates with drier conditions in the Yucatan and equatorial East Africa ...
... and strengthens regional precipitation, such as the monsoons.

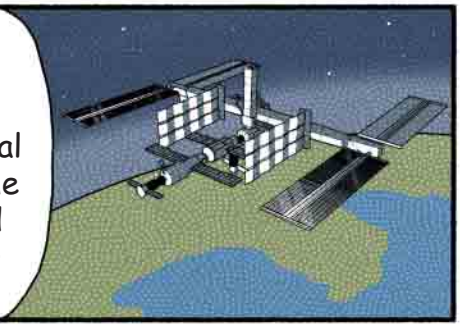

These phenomena are also affected by the Sun?
Other processes can affect them too ... things like changes in the ocean circulation that can occur with cycles similar to the Sun's.


I never realized that the Sun influences our life so much!
I am not surprised. We tend not to pay attention to slow climate changes.
But, how do we feel if these phenomena become of practical concern when we are threatened by changes in climate and the ozone layer?
Oh, no!
Archaeological and paleo-climate records suggest that ever since the earliest civilizations formed around 12000 years ago, climate changes, possibly linked with the Sun, may have caused, or at least contributed to, societal deterioration.
Droughts in the Yucatan peninsula appear to have a 208-year cycle in phase with decreased levels of cosmogenic isotopes, indicating periods of higher solar activity.
These droughts, in addition to famine and political upset, may have caused the decline of the Mayan civilization around AD 800.
Droughts...! Decline of civilization...!
Our daily life may be threatened by disorder.
Wa, water ...
We have to keep these solar effects in perspective. Contemporary global warming is primarily from human activity.
The solar-driven ozone cycle is comparable in magnitude to the anthropogenic decline. We have to view data calmly.

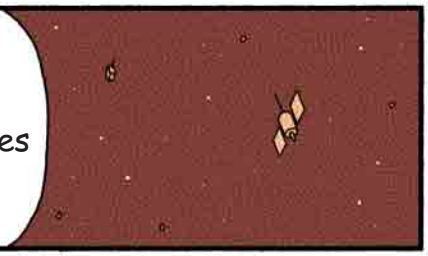
We have so far considered long-term changes in the Sun-climate system. Let's now look at how the Sun can affect us in other ways, on shorter times.

The upper atmosphere beyond the Earth's surface is susceptible to more immediate effects of Sun-Earth system variability.

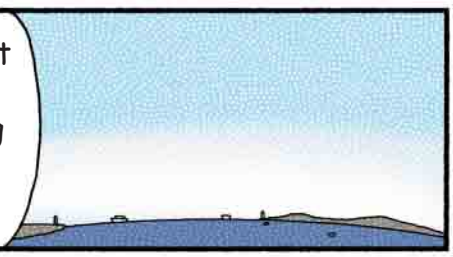
After solar flare eruptions, energetic particles can damage space-based technological systems and threaten the health of astronauts and airplane passengers over polar regions.



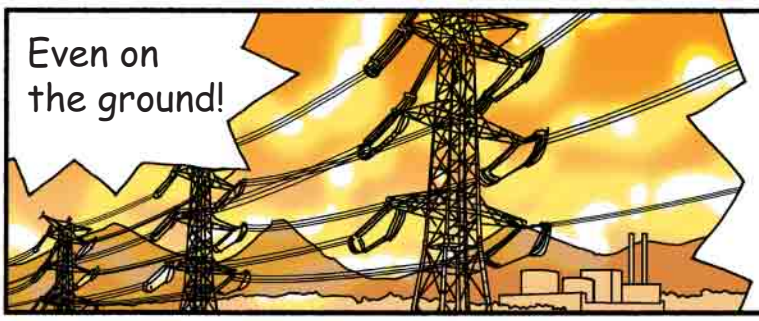
Solar-driven atmospheric density fluctuations can alter the orbits of satellites in low-Earth orbit.



Solar flares also interrupt wireless navigation and communication by altering the electron density in the ionosphere.



Even on the ground!



Induced ground currents can weaken the electric grid and oil pipelines, potentially causing serious failures.

To avoid such problems, we must improve our understanding and develop appropriate strategies.

Understanding the Sun-Earth system is equivalent to understanding our own home in space beyond the surface where we live now.

That is why we are working hard.

Aha!

Mol and Mirubo felt the close link between the Sun and Earth.

What is the Sun-Climate Relationship?

It's obviously warmer when the Sun is shining, so why is the Sun-climate connection so controversial?

A natural question! Temperatures change from day to night and summer to winter because as the Earth rotates on its axis and orbits the Sun, solar radiation is deposited at different geographical locations. When averaged over the whole globe for a year, the temperature remains constant. But if the Sun's brightness changes, the altered solar energy causes a new annual average temperature, and changes the climate.

The Sun's total brightness is called the solar "constant"… does this actually change?

Correct! The Sun's total brightness - the sum of radiation over all wavelengths - varies with an 11-year cycle of amplitude about 0.1% (from minimum to maximum) in recent times. Ultraviolet radiation varies more than visible and infrared radiation. Only by flying very accurate, stable solar radiometers on spacecraft above the Earth's atmosphere has it been possible to measure these changes.

Interesting, indeed. What do sunspots have to do with the Sun's brightness?

Another good question! When the Sun is active, such as near the maxima of the 11-year cycle, there can be many sunspots on its surface. Sunspots are dark, and their decreased radiation reduces the Sun's net brightness. But, solar activity also produces features where radiation is enhanced. Called faculae, these features more than compensate for the sunspot darkening, and produce a net overall increase (about 0.1%) in total brightness during the solar cycle.

The brightness changes seem small – how much do they influence climate?

The change of 0.1% is small only in a relative sense. The increase in energy that the Sun radiates between the minimum and maximum of the 11-year cycle produces a climate forcing equivalent to that from increased concentrations of greenhouse gases over the same period. Earth's global surface temperature increases by ~0.1°C during the solar cycle... some regions warm more than this and other regions actually cool, because of altered dynamical motions in the atmosphere and ocean. Evidence from the past suggests that rainfall and drought may be particularly sensitive to even small changes in solar radiation.

Can the Sun's changes explain global warming in the past century"?

The IPCC* (2007) assessment estimates that the growth of greenhouse gases since 1750 exerts a ten times larger influence on climate than changes in the Sun's brightness. Whereas solar-induced changes in surface temperature since 1880 are of order 0.1°C, the man-made global warming is now more than 0.65°C.

If the Sun declines into another minimum in activity – like that in the 17th century - might this decreased brightness produce cooling to counter future global warming?

Changes in solar brightness are very likely limited to a few tenths percent and the associated global surface temperature changes to a few tenths °C. The warming from doubled CO_2 is more than an order of magnitude larger - in the range 4°C, so a Maunder-Minimum type decline in solar brightness would counter at most only a small fraction (a few percent) of the expected anthropogenic warming.

Regardless of whatever is affecting our climate, let's hope it doesn't change too much.

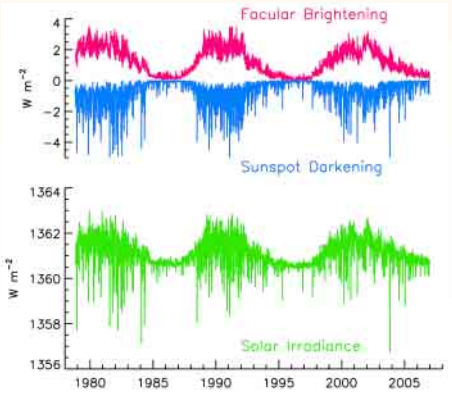
* IPCC: Intergovernmental Panel on Climate Change

Understanding the Sun and Climate

The Sun is a middle-aged star, and the Earth is a planet which orbits it, 150 million km away. Scientists have long been curious about whether changes in the Sun's energy output might affect the Earth. Today, concerns about global warming provide a new imperative to investigate natural causes of climate change, so as to properly isolate them from the effect of increasing anthropogenic gases.

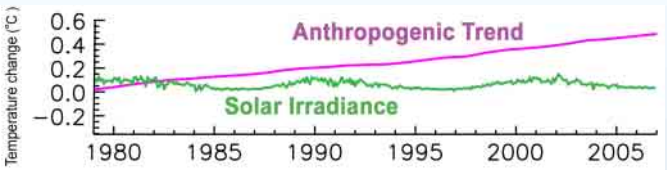
Heated by nuclear fusion inside its core, the Sun's surface radiates electromagnetic energy with a spectrum that peaks at visible wavelengths. This radiation heats the Earth's surface to about −18°C. Global average temperatures are 33°C warmer because greenhouse gases in the atmosphere trap infrared radiation that the Earth's surface radiates back to space. The balance between incoming solar radiation and outgoing infrared radiation establishes the Earth's equilibrium surface temperature. Altering this radiation balance - by changing the Sun's radiation or the concentration of greenhouse gases in the atmosphere - causes the climate to change.

High precision radiometers on Earth-orbiting spacecraft begun measurements of the Sun's brightness in the late 1970s and soon found that it varied continuously. The overall increase in brightness during high solar activity tracks the accumulation of bright faculae, adjusted for sunspot blocking. Models that combine the competing effects of sunspot darkening and facular brightening can account for ~85% of the measured variations. But the irradiance record is too short to determine whether the changes are constrained to the 11-year cycle or if longer term changes are also occurring. For this, a much longer and uninterrupted space-based time series is needed.

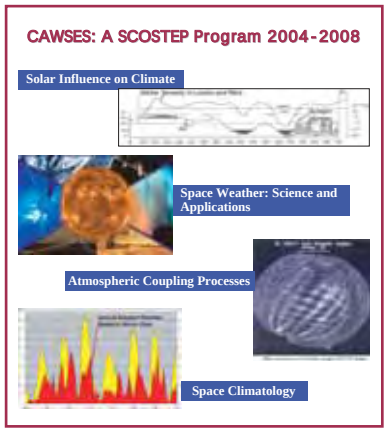


The irradiance cycle arises from the competing effects of sunspots and faculae.

Changes in the Sun's brightness are but one of many causes of climate change. Volcanic eruptions, the El Niño Southern Oscillation and other ocean-atmosphere interactions, land cover changes, and altered concentrations of troposphere aerosols and greenhouse gases can all influence climate. Paleo climate records and climate model simulations generally agree that over the thousand years before the industrial period, volcanic eruptions and solar brightness changes were the primary influences on climate, producing changes of a few tenths °C in global temperatures. Both recent and paleo data suggest that the hydrological cycle - rainfall and drought - is especially sensitive to changes in solar brightness, and may involve similar interactions between the ocean and atmosphere that produce the El Niño Southern Oscillation. The results are motivating improvements and expansions of general circulation climate models; improvements that may enable more reliable forecasts of future climate change.



Both solar irradiance and anthropogenic causes have affected Earth's global surface temperature over the last 30 years. Shown are the changes in these two components, estimated from multi-regression analyses. The two curves are normalized as zero at 1976 (solar minimum).



Climate and Weather of the Sun-Earth System (CAWSES)

CAWSES is an international program sponsored by SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) and has been established with the aim of significantly enhancing our understanding of the space environment and its impacts on life and society. The main functions of CAWSES are to help coordinate international activities in observations, modeling and theory crucial to achieving this understanding, to involve scientists in both developed and developing countries, and to provide educational opportunities for students at all levels. The CAWSES office is located at Boston University, Boston, MA, USA. The four science Themes of CAWSES are shown in the figure.

http://www.bu.edu/cawses/
http://www.scostep.ucar.edu/

Solar-Terrestrial Environment Laboratory (STEL), Nagoya University

STEL is operated under an inter-university cooperative system in Japan. Its purpose is to promote “research on the structure and dynamics of the solar-terrestrial system,” in collaboration with a number of universities and institutions both in Japan and abroad. The Laboratory consists of four research Divisions: Atmospheric Environment, Ionospheric and Magnetospheric Environment, Heliospheric Environment, and Integrated Studies. The Geospace Research Center is also affiliated to the Laboratory to coordinate and promote joint research projects. At its seven Observatories/Stations, ground-based observations of various physical and chemical entities are conducted nationwide.

http://www.stelab.nagoya-u.ac.jp/

はやのん Hayanon

Graduated from the Department of Physics of Ryukyu University, Hayanon, a writer and cartoonist, has contributed a number of serials in popular magazines on the basis of her strong background in science and computer games. Her consistent writing style, expressing a love for science, is well accepted.

http://www.hayanon.jp/

子供の科学 Kodomo no Kagaku (Science for Kids)

Kodomo no Kagaku, published by the Seibundo Shinkosha Publishing Co., Ltd. is a monthly magazine for juniors. Since the inaugural issue in 1924, the magazine has continuously promoted science education by providing various facets of science, from scientific phenomena in everyday life to cutting edge research topics.

http://www.seibundo.net/

“What is the Sun-Climate Relationship?!” is published with cooperation of “Kodomo no Kagaku.” Mol and Mirubo thank Caspar Ammann and Art Richmond for their help in preparing the English version of our story.

Produced by the Solar-Terrestrial Environment Laboratory, Nagoya University and the Scientific Committee on Solar-Terrestrial Physics in conjunction with the CAWSES program.
July 2008