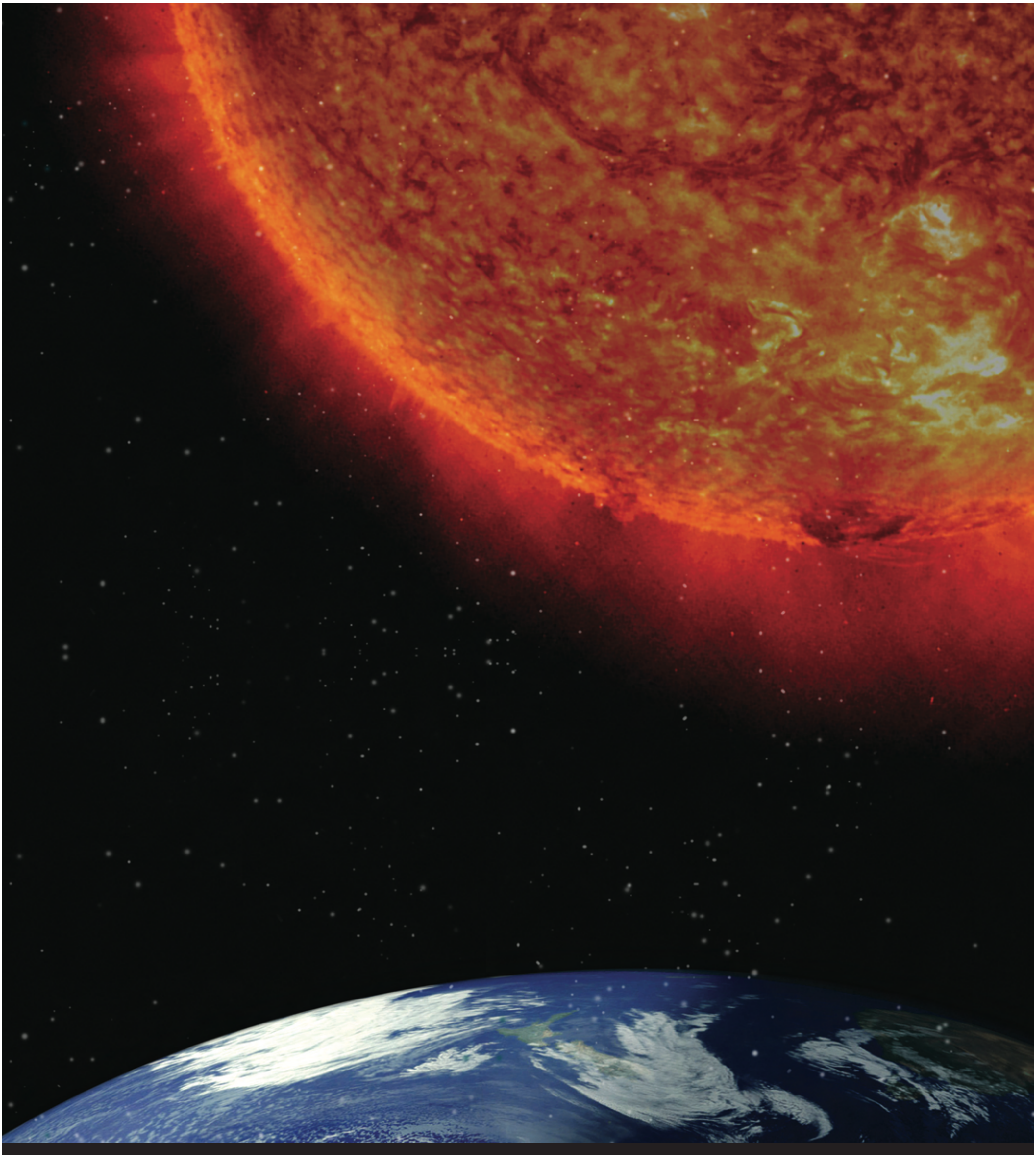

Radiation in the form of heat and light provides almost all of the energy transferred between the Sun and the Earth, shown here in close proximity. The diameter of the Sun is actually about 100 times larger than that of the Earth, and the distance that separates them—about 93 million miles—is equal to well more than 100 solar diameters. Thus the Earth seen from its constant benefactor would appear little larger than a dot in the sky.

FLUCTUATIONS IN SOLAR RADIATION AT THE EARTH

Changes in Total Solar Irradiance

It has long been known that the face of the Sun changes from day to day with the coming and going of sunspots and faculae on its white-light surface; that the outer layers of the solar atmosphere—the chromosphere and corona—are even more dynamic and variable; and that solar explosions and eruptions are everyday occurrences on the star. But to what extent do these transient features alter the amount of solar energy we receive at the Earth, 93 million miles away?

For example, how great of a surge can we expect when the flood of x-rays and extreme ultraviolet radiation from an explosive solar flare arrives at the Earth, in eight minutes time? Or seven minutes after that, when solar energetic protons, propelled outward at half the speed of light, come upon us from the same cataclysmic event on the Sun? How much added energy must the outer atmosphere of the Earth absorb when an incoming blob of charged solar plasma, ejected from the corona a few days before, becomes magnetically connected—like the accidental contact of two hot wires—to our own magnetosphere?

Or the most commonly-asked question regarding the Sun (which remained unanswered and unanswerable for more than 360 years after Galileo first found sunspots): What is the effect— if any—on the total amount of heat and light we receive when sunspots come and go?

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Since sunspots appear darker than the surrounding photosphere, they have obviously reduced the flow of radiation from the restricted area of the solar disk that each one covers. Faculae, which are brighter than the surrounding surface, clearly add locally to the total radiation emitted.

Could it be that what one takes away, the other immediately restores? That each sunspot simply acts as a plug to deflect without stopping the flow of solar energy that pushes inexorably upward from deep within the star?

Were this the case, the total solar irradiance—the amount of energy that the Sun delivers in all wavelengths at the top of the Earth's atmosphere—might indeed be called, as long it was, the "solar constant."

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We know now, based on more than a quarter century of direct measurements taken from space, that there is and never was a solar constant. The total amount of energy emitted from the Sun varies on all scales of time, from seconds to years, as does the energy emitted in any of the different spectral components that contribute to that sum. Everything changes, all of the time: the radiative energy emitted in x-ray, ultraviolet, visible, infrared, and radio wavelengths as well as the energy carried outward from the star in the form of energetic atomic particles. All of them respond to varying magnetic activity on the surface of the Sun.

We also know that the flow of solar energy in each of these components—and their sum—increases when the Sun is more active, peaking at times of maxima of the 11-year solar cycle, only to fall back down again in years of minimum activity.

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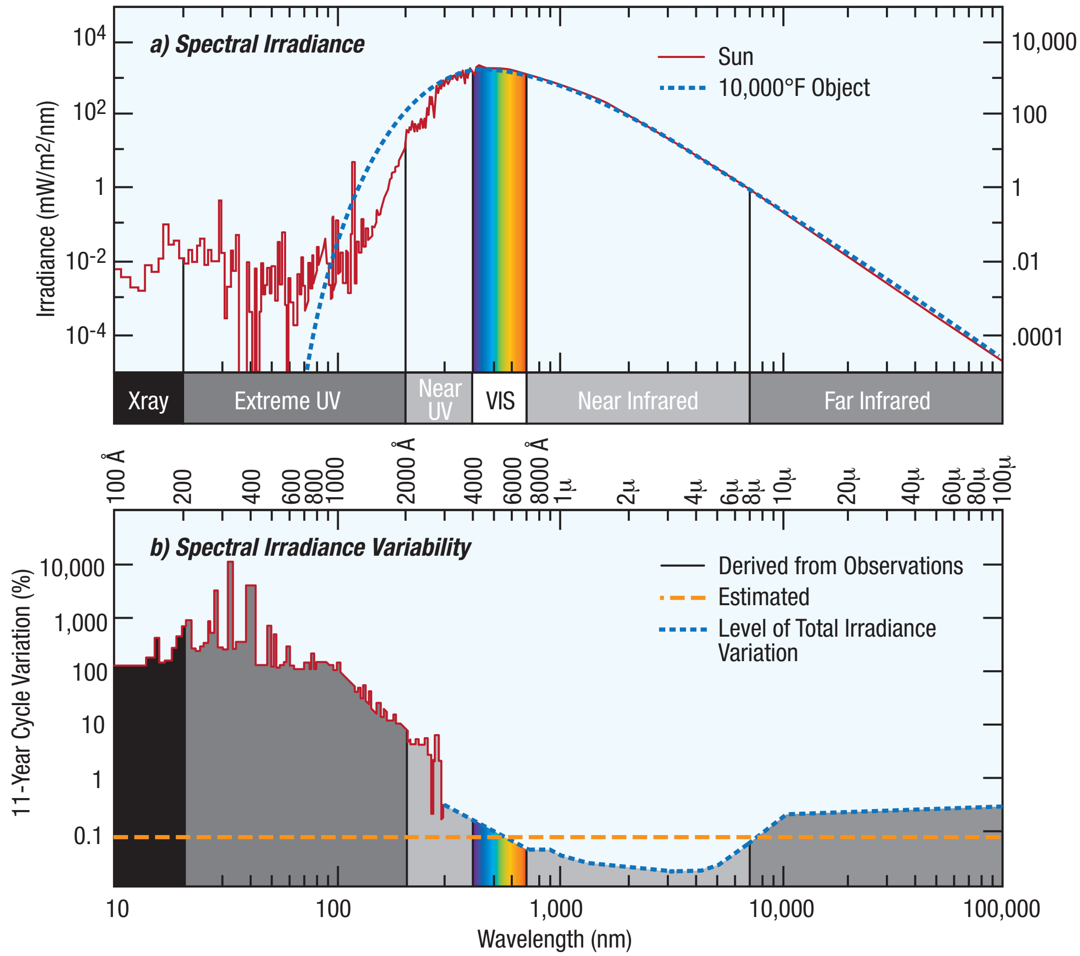
The overall level of *solar activity* varies as well on decadal periods of time, changing by a factor of five or more from one 11-year cycle to the next, when measured in terms of the numbers of sunspots seen on the Sun in the years around the maximum of each solar cycle. There are weak cycles and strong cycles, and prolonged periods in which the cycles are (1) persistently stronger (as during much of the last century); (2) weaker (as in the first three decades of the 19th century and at the turn of the 20th); and (3) almost but not quite absent altogether (as during the 70-year period that ended in 1715.) There is also some evidence of a longer solar activity cycle of about 80 years and another of more than a thousand years.

What is still not known and needs to be found is the extent to which these longer-term changes in solar behavior—spanning periods counted in decades to centuries—affect the total energy that the Sun emits, since the period for which we have actual measurements is as yet so short.

Precision radiometric measurements of the total heat and light and other radiation received from the Sun can be made only from above the Earth's atmosphere. This technically-challenging task was initiated on a continuing basis in 1978 and has been sustained since that time by a series of dedicated instruments on different solar spacecraft. When properly intercalibrated and pieced together, these invaluable data provide a continuous day-to-day record of the Sun's most vital sign which now extends for more than a quarter-century.



The spectral distribution of solar radiation and its variablility. (a) Upper figure: Red line: the amount of solar electromagnetic radiation in different wavelengths that falls on the top of the Earth's atmosphere, expressed in milliwatts per square per nanometer wavelength, compared with the relative amount of radiation (dashed blue line) expected from an ideal radiator at a temperature equal to that of the Sun's visible, photospheric surface. The excess solar radiation seen at the shortest wavelengths originates in higher regions of the solar atmosphere (chromosphere and corona) where the temperature is much higher. (b) Lower figure: the percentage variability of solar radiation in these wavelengths. In the visible and near-infrared spectrum the variation is at most about 0.1%, and only slightly more in the far infrared. The greatest variation is not surprisingly found in the short-wave radiation that emanates from the Sun's more volatile upper atmosphere. There the variation is several percent in the near-ultraviolet, 100% in most of the extreme ultraviolet and x-ray region, and up to more than 1000% in narrow wavelength regions corresponding to the wavelength-specific radiation (called spectral emission lines) of highly-ionized atoms, such as the very strong emission line at a wavelength of 30.4 nanometers (or 304 Ångstroms) coming from ionized helium.

Variability in Different Parts of the Spectrum

More than 90% of all the energy that leaves the Sun comes to us in the visible and near-infrared regions of the spectrum, in the form of light and solar heat. Both of these two components vary in step and in phase with changing solar activity: changing by at most a few tenths of a percent in day-to-day excursions and more slowly and systematically in the course of the 11-year solar cycle. Though small in terms of other climate modulators—such as cloud cover—that more forcibly and more randomly alter the amount of radiation received at the Earth's surface, these more persistent changes in external solar forcing are sufficient to leave discernible, 11-year marks on the surface temperature of both the lower atmosphere and the oceans.

Slightly less than 10% of the Sun's total output of energy comes to us in the form of near-ultraviolet radiation, which dictates the production of ozone and through that process heats the stratosphere. Since it originates at a higher and more active level in the Sun's atmosphere, solar radiation in this invisible part of the spectrum is more variable than the visible and near-infrared parts. Its response to changes in magnetic activity on the Sun is also much greater, varying by as much as 10%.

In addition, the photons that carry radiation in the near-ultraviolet are considerably more energetic and as such are potentially hazardous to life: with the potential of immediate damage to our eyes, skin and other human tissue, and more subtly to our immune system. Although most of the solar near-ultraviolet radiation incident upon the Earth is absorbed by ozone, a small fraction—more at higher altitudes and at lower latitudes—slips by the ozone filter in the sky and makes its way to the surface of the Earth to do its damage to those exposed.

The extreme ultraviolet (EUV) and x-ray radiation from the Sun arises from the progressively higher temperatures of the upper chromosphere, transition zone and corona. The structure and make-up of these upper reaches of the Sun are highly variable, as is the EUV and x-ray radiation from the Sun as a whole, fluctuating by an order of magnitude or more.

Solar EUV and x-ray radiation are also far more energetic than the near-ultraviolet and potentially more lethal. And even though these most energetic rays make up but one ten-thousandth of the total energy emitted by the Sun, they are sufficient to exert almost complete control of the thermosphere and the ionosphere.

SOLAR ENERGY RECEIVED AT THE EARTH

FORM	TOTAL ENERGY IN WATTS PER ACRE AT THE TOP OF THE ATMOSPHERE	FRACTION THAT REACHES THE SURFACE	FRACTION OF TOTAL ENERGY RECEIVED	VARIABILITY
TOTAL IRRADIANCE	5500	60%	~100%	0.1%
Near infrared	2800	55%	51%	0.05%
Visible	2200	75%	40%	0.1%
Near-ultraviolet	490	40%	9%	1%
Far-infrared	10	20%	0.14%	0.1%
Far-ultraviolet	.5	0	0.01%	15%
EUV and x-ray	.2	0	0.005%	up to 200%
PARTICLES				
Solar protons	0.002		negligible	up to x100
Solar wind particles	0.0003		negligible	up to x30
Galactic cosmic rays	0.000006		negligible	20% due to solar modulation

The Sun sends out radio waves as well, and in all directions, which can be clearly heard using a directed antenna as crackling static across the full span of the radio frequency spectrum. But the radio emission from the Sun is of little consequence in terms of direct terrestrial impacts since it carries so little energy, even during explosive flares, when the Sun's radio emission increases by many orders of magnitude. What the Sun emits in these very long wavelengths is, nevertheless, of considerable value as a diagnostic tool for remotely probing and monitoring the solar corona and transition zone, where radio frequency radiation originates, and as an alternate index of solar activity.

The largest spikes in the near-ultraviolet, EUV and x-ray radiation from the Sun come from the eruption of explosive solar flares, in which concentrated magnetic energy is suddenly and catastrophically converted into heat and light and short-wave radiation.

At these times the flaring region on the solar disk brightens dramatically in all parts of the spectrum, with the greatest increase in the shortest wavelengths. In EUV and x-ray radiation the burst of radiation is so intense that it dramatically increases the total radiation in these wavelengths received from the entire disk. In white, visible light this is almost never the case, and when it does—during the very rare occasions when a so-called white-light flare occurs—the brief increase in the total visible radiation from the Sun is no more than 1%.

Although the energy released at the site of the flare can equal the detonation of a tightly-clustered pack of 100,000 atomic bombs, the direct effect on the total amount of solar energy received at the Earth—a very small target at a very great distance—is to add, but briefly, about four watts to the more than 5540 kilowatts per acre that the Sun continually deposits in the form of light and heat.

Effects of the Sun's Rotation

The 27-day rotation of the solar surface has no effect on the total amount of radiation the Sun sends outward in all directions. But it plays a major role in modulating the amount the Earth receives by exposing us each day to a different part of the variegated surface of the radiating photosphere.

Were the Sun to spin much more slowly and, like the Moon, keep the same half of its surface turned always toward us, the energy we receive would still vary in response to both eruptive events and the birth and evolution of sunspots and faculae, which come and go in matters of days to weeks.

Solar rotation superposes on these intrinsic solar changes a more rapid and complex modulation, as new and different patchworks of sunspots and faculae are rotated into and then out of our view. In the process the Sun rolls out for us a panoramic display of its entire surface, continually updated and repeated for us—should we have missed all or part of the first show—fourteen times each year.

Were we unable to see the surface of the Sun we could still determine its average rate of rotation from ongoing observations of solar radiation received at the Earth in the energetic ultraviolet. As long-lived active regions are repeatedly carried across the face of the Sun by solar rotation these short-wave hotspots on the visible disk would appear in a recording of ultraviolet flux from the Sun like a sweeping beam of light from a lighthouse.

The effect on the ultraviolet radiation we receive introduces a related 27-day modulation in the amount of ozone in the stratosphere, which is largely controlled by short-wave solar radiation.

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The marks of solar rotation are also seen in continuous measurements of the total solar irradiance during the passage of large sunspots across the solar disk.

A large sunspot coming into view at the eastern or left-hand limb of the Sun will first appear very much flattened in one dimension due to the spherical shape of the Sun. If the spot is *circular*, it will first appear to us in a telescope as a dark vertical *line*, and in succeeding days, as more and more of its true area is turned toward us, as a flattened *oval*. As it moves with the Sun's rotation across the face of the Sun we are shown more of its true shape and size, which are fully revealed only when the sunspot reaches the central portion of the solar disk.

This imposed "foreshortening" effect can be quite evident in the record of total solar irradiance during the time that a large sunspot is carried by rotation across the face of the Sun. The amount of energy a sunspot takes from the total solar energy received at the Earth is proportional to its *projected area* on the solar disk: greatest when the spot reaches the central region of the disk and least when it lies near either limb. Thus as it is carried across the Sun by solar rotation a single large sunspot or sunspot group will often appear as a distinctive V-shaped notch in a continuous record of total solar irradiance.

Effects of the Earth's Orbit

A number of other influences, unrelated to the Sun itself, alter both the total amount of solar radiation the Earth receives, and how it is distributed over the spherical surface of the planet. Some of these, arising from the non-circularity of the Earth's orbit and a congenital tilt in its axis of rotation, continually modulate the amount of solar energy that arrives on any day, and any place.

Others, such as atmospheric absorption and reflection from clouds and aerosols—the middlemen in the radiative transfer business—take their often heavy cut from the amount that enters the top of the atmosphere as it streams downward toward the surface of the Earth. In the end, only about half of the all the energy that the Sun delivers on our doorstep—at the very top of the atmosphere—will ever make it to the ground.

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The fact that the rotational axis about which the Earth spins is not exactly perpendicular to the plane in which our planet circles the Sun introduces a dramatic annual modulation in the solar energy we receive. This considerable imperfection tilts the Earth's North and South Poles for half of the year *toward* the Sun and for the other half *away* from it. This produces a regular change in the height to which the Sun climbs each day in the sky, and through this a smooth annual variation in the number of hours of sunshine. From this tilt in the Earth's rotational axis come the seasonal rhythms which for eons have so strongly directed the course of life on the planet.

The magnitude of these seasonal changes obviously depends on one's latitude and the angle—currently 23½°—at which the Earth's axis is tilted. But unlike the globes on our desks and tables, the angle of inclination of the real Earth was not permanently fixed at The Factory.

The tilt of the actual, spinning Earth is nudged toward larger or smaller angles of inclination by the combined gravitational pulls of the other planets and the Moon. Because these change with time, the tilt angle slowly oscillates back and forth between limits of 22 and 25°, completing a full cycle in about 41,000 years. This too, has important climatic impacts since it affects how incident solar energy is apportioned over the spherical Earth.

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Similarly, although we often think of the Earth's orbit as circular, the path we actually follow in our annual trip around the Sun is in truth slightly elliptical: an oval, not a circle, which in the present era takes us about 3 million miles nearer to the Sun at closest approach than half a year later, when we are farthest away. This annual variation of about 3% in the distance that solar radiation must travel to get to us—which ranges from 91½ to 94½ million miles—produces an annual modulation of almost 7% in the total radiation the Earth receives: an annual change that is a hundred times larger than any variation of purely solar origin.

The elliptical shape of our orbit is another consequence of the gravitational pulls of the Moon and the other planets on our own movement around the Sun. At present, the eccentricity or non-circularity the Earth's orbit—a measure of its departure from a perfect circle—is slightly less than 2%. But this, too, slowly varies with time, oscillating in the course of about 100 thousand years between nearly zero (when for a limited time our orbit is indeed a divinely perfectly circle) to an upper limit of about 6%.

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The climatological impact of variable eccentricity is much affected by a *third* significant variable of our orbit about the Sun: namely, the *times* of the year when the elliptical path takes us closest to our parent star, and farthest away. These times of maximum and minimum intensity can fall in any part of the calendar, and do, following a cycle of about 22 thousand years. Like the other perturbations, it too is dictated by the changing pulls of the other planets and the Moon as these other bodies trace out their own celestially imperfect orbits.

In the present era the Sun is closest to the Earth in January and farthest in July. Thus the effect on the Northern hemisphere is to dilute, somewhat, the intensity of the seasonal changes that follow from the tilt of the Earth's axis. In the Southern hemisphere, approaching closer to the Sun in January (there, in early summer) and farther from it in July (in winter) has quite the opposite effect.

In the Southern Hemisphere the impact on seasonal climate of turning up the heat in summer and turning it down in winter is at present not as severe as in the Northern Hemisphere. There the effect is appreciably dampened by the current placement of the ever-drifting continents: specifically, the happenstance in the present era of more extensive oceans in the Southern hemisphere and the presence at the South Pole of a very large ice-covered continent, both of which provide thermal inertia.

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These slow and subtle changes in the orbit and inclination of our planet—known as the Milankovitch effect—act together to reapportion in time and reallocate in space the continuous flow of energy that the Sun delivers to the Earth. And though small in absolute terms, the internally-amplified climatic impacts of these changes appear to be sufficient to have served as a pacemaker for the coming and going of the major Ice Ages throughout the last million years of Earth history, as revealed in repeated patterns of ocean temperature obtained by paleo-oceanographers from the analysis of deep-sea cores.

Lost in Transit: The Fate of Solar Radiation in the Earth's Atmosphere

All else that modulates the amount of solar radiation that streams down upon the Earth—including all variability at the source itself and all short and long-term consequences of our orbit about the Sun—is dwarfed by what happens in the atmosphere itself: in but the last few hundred miles of a long, long journey. In its passage from the top to the bottom of the ocean of air, only a little more than half of the solar energy that falls upon the upper atmosphere will reach the solid surface and oceans of the Earth. The rest will be consumed as it speeds downward through the air, or reflected back towards the Sun.

About 30% of all solar radiation that arrives at the top of the atmosphere is immediately rejected by the planet and returned, unused, back into the dark of space: reflected mostly in the lower atmosphere by clouds and other suspended particles or at the surface by highly reflective water, ice and snow and different types of land cover.

The remaining 70% is put to use: the sum of the 50% that is absorbed by the surface to directly heat the planet and 20% that is selectively absorbed by atoms and molecules of air, mostly high in the atmosphere, or selectively scattered in the lower atmosphere to illuminate and color the sky. Included in the 70% is all the energy in the x-ray and extreme ultraviolet region of the spectrum, which is absorbed in the thermosphere and mesosphere; almost all of the near-ultraviolet, absorbed by ozone in the stratosphere and troposphere; and some of the infrared, absorbed in the same region by water vapor, carbon dioxide and the other molecular greenhouse gases.

All of these deductions vary from place to place and on all scales of time, as they together reduce and modulate the solar energy that ultimately reaches us at the bottom of the ocean of air.