Chapter 2
Exergy-Entropy Process of Global Environmental System

Abstract All of the built environmental spaces, in which we humans spend more than 90 % of the period of our life, are surrounded by the global environmental system. Therefore, we discuss here briefly how the global environmental system works as "exergy-entropy" process and how the average ground surface temperature is kept at 15 °C. We first clarify that an "exergy-entropy" process functions in cycle taking the following four fundamental steps: exergy supply; exergy consumption; entropy generation; and entropy disposal. With this way of looking at the global environmental system in mind, a couple of calculations on the average ground-surface temperature are made to demonstrate the importance of water and air circulation within the atmosphere.

Most of us are familiar with a picture of the Earth taken from a spaceship, which shows us the spherical shape with the colors of blue as the sea, light-brown as the desert area, and above all the patches of white as the clouds.

Atmospheric temperature near the ground surface is different from regions to regions and also different from one season to another in one certain region. On the one hand, in the regions near the Arctic or the Antarctic, the temperature ranges from −35 to 10 °C, while on the other hand, near the equator, it ranges from 20 to 35 °C in tropical forest regions and from 10 to 45 °C in arid regions. In a region such as Yokohama in Japan with middle latitude, atmospheric temperature near the ground surface ranges from 0 to 34 °C.

The average temperature of all these regions with all seasons turns out to be about 15 °C. This average global temperature remains almost unchanged from year to year during the period of several decades, which is very short compared to the history of the Earth.

The Earth is always irradiated and thereby heated by the Sun whose surface temperature is 5700 °C, while at the same time it is always cooled by the Universe whose radiant temperature is about −270 °C, only 3 °C higher than the absolute zero of thermodynamic temperature.

M. Shukuya, *Exergy*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-4573-8_2,

The average global temperature of 15 °C is the result of such simultaneous heating and cooling. We call this mechanism as the global environmental system, within which all of the ecological systems including the built environment are working.

2.1 What is the Problem in So-Called Global Environmental Issues?

The global temperature was not constant throughout the four-and-a-half-billion-year history of the Earth. Geological, meteorological, and biological events happened on the Earth in the past have led to the contemporary annual average global temperature of 15 °C.

The condition that the global temperature tends to decrease is called "global cooling" and that the global temperature tends to increase "global warming". Such conditions seem to correlate well to the average carbon-dioxide concentrations within the atmosphere. Carbon-dioxide molecules flying around within the atmospheric air, whose concentration is only the order of 0.03–0.05 % though, play a crucial role in how much of the long-wavelength thermal radiation emitted toward the upper atmosphere from the ground surface is absorbed.

The fact that the carbon-dioxide concentration within the atmosphere has increased gradually over the last 40 years looks consistent with the atmospheric temperature having arisen slightly. Its most likely reason has been believed by many people that the emission of carbon-dioxide due to the burning of fossil fuels that enables the contemporary human societies to run, although we must admit that we hardly know whether the emission of carbon-dioxide is really the principal reason of the global warming.

There are quite a few phenomena seemingly caused by global warming, such as the rise of sea-water level, the decrease in forest areas bringing about poorer biological diversity and others, most of which have come to be known by people through various media like newspapers, TV programs, and Internet homepages. But what we have to be careful is that they are all indirect knowledge; most of us have not seen and confirmed those phenomena directly with our eyes. Therefore, it is necessary for each of us to have wisdom to be able to judge which pieces of information are true and what kinds of actions we should take.

We humans, one of the biological species, at present have the largest population ever grown and a large number of people are now living in urban areas. This is due mainly to the fact that the science, one of the human activities, developed very rapidly over the past 300 years and the associated technology advanced very much in the nineteenth and twentieth centuries. Advancement in science and technology leading to the urbanization is represented by the electricity production with fossil fuels including natural gas, uranium fuels, and also the production of various artificial goods.

We can easily list up the products brought by the contemporary science and technology: electric lamps mounted on the ceilings, heat-pump air conditioners hung on the interior walls, TV sets in living rooms, personal computers on the desks at homes and at offices, refrigerators in the kitchens, cars in the garages, mobile cellar phones, and so on. We can hardly imagine a life style without them. The recent accelerating urbanization of human beings reflects very well the characteristics of such contemporary science and technology.

On the one hand, the assets that we can have in urban areas are the convenience and comfort given by the most advanced technologies. On the other hand, those you can have in rural areas is the freshness of water, air, and foods brought by local mountains, forests, lakes, rivers, and sea. The former is brought by "artificiality" and the latter by "nature". Since the artificiality looks worthwhile for most of the people much more than the nature which can be sometimes very harsh, more and more people have come to live in cities and thereby some of the cities have grown to be gigantic. This trend, the growing urbanization, causes more intense use of fossil fuels and other resources including foods in the cities.

Waste heat and rubbish produced by big cities due to intense human activities must be discarded inevitably according to the law of nature as mentioned in Sect. 1.3, otherwise those cities can hardly sustain their activities. The problem is that the amounts of waste heat and also the chemical characteristics of the rubbish seem to have reached the level of endangering the sustainability of the nested structure of environmental spaces. But, the trend of human activity as a whole following the direction taken by our society for the last several decades is still growing. That is the present situation of our global society at large, which we should share to recognize and try to make a change. Under this circumstance, we need to find a moderate rate at which the environmental capacity allows our society to use valuable fossil fuels and other raw materials.

Whether it is global warming or global cooling, a sudden big change in the rate at which our society uses fossil fuels and other resources might cause a catastrophe, maybe meteorological, geological, or biological including human-societal.

Let us imagine a case of global cooling. If a nuclear war had happened, a large amount of radioactive particles would have spread over the atmospheric air all over the Earth. Those particles would become fine cores at which water vapor can condense and grow into many small droplets of liquid water and hence more clouds emerge in the atmosphere. This could cause the decrease in the amount of solar radiation available on the ground surface so that the global temperature may start to decrease.

We do not know whether it can really happen or not, but it is too absurd to do such experimentation. Unfortunately some politicians and technocrats in some countries having nuclear weapons or such capability are likely to suggest that the use of such terrible weapons is necessary for a certain case in which they feel a threat from other countries. It is very important for each of us, as an individual, a very ordinary citizen, to be wise enough to let abandon the use of, and hopefully the possession of such weapons, whether they are large or small, and also capable facilities.

Let us next imagine a case of global warming. What corresponds to the nuclear war raised in the case of global cooling is the use of fossil fuels and condensed uranium to produce electricity and also the use of various raw materials to produce a variety of artificial goods for everyday life. A lot of fossil fuels and raw materials are also used in the production of nuclear weapons so that the difference in the total amounts of fuels and materials between the case of nuclear weapons and the case of electricity and artificial-good production must be marginal. Totally different are their rates, the speeds. The rate at which the fuels are consumed in the case of electricity and artificial-good production is much smaller than that in the case of nuclear bombing.

On the one hand, a huge rate of exergy consumption due to nuclear explosion might cause global cooling mentioned above, while on the other hand, a comparatively smaller rate of fossil-fuel consumption might cause global warming mentioned above. Which of these two occurs seems to be a typical example of complex phenomena, in which the result can be quite different depending on their initial conditions to be given.

There is a dispute whether the use of nuclear power plants that emit little amount of carbon-dioxide gas into the atmosphere should be promoted more or not. The nuclear power plants in operation may not emit carbon-dioxide gas much, but inevitably produce the nuclear wastes. One-day operation of a nuclear power plant with its capacity of 1 GW (=10^6 kW) electricity production inevitably generates 3.3 kg of nuclear wastes [1], that is 1000 kg/year, which necessitate their very careful management over a long period of time exceeding a couple of human generations. Taking this into consideration, we should be much more modest in the use of nuclear power plants and should move toward being rather free from our too-much reliance on them.

It was early 1990s when “global warming” became one of the issues raised in not only scientific but also political discussions. Now is more than 15 years since then, but the fact that we should be sensitive and surprised is that the rate of fossil-fuel use has never fallen but instead has been increasing over this period of 20 years in spite of the fact that many people believe the fossil-fuel use being the most likely the cause of global warming.

The present rate of fossil-fuel consumption has been said very large, but it is much smaller than the rate at which a nuclear-bomb explodes; the rate of the latter is so large that the whole cities of Hiroshima and Nagasaki were destroyed and so many people in the regions passed away within a very short period of time and those survived have had to suffer from pains not only physically but also mentally.

We may not be sensitive enough to the danger likely to be brought by a much smaller rate of fossil-fuel consumption than that of nuclear-bomb explosion. Our mind has not yet grown to be wise enough to sense the danger which may be brought by our present life style and to change it into a humble one. Or maybe the inertia of the present human society with respect to the consumption rate is so large, but cannot be sensed as we hardly sense the speed of a bullet train at a rather constant speed of 300 km/h. It may take still very long before the rate of exergy consumption in our society starts to decrease.

Minding the global environmental issue emerges uniquely at the highest level of the function of human brains, which cannot be shared by that of other animals. The present technology has allowed us to have various pieces of information such as the photographs of Earth taken from a spaceship, the numerical data characterizing the atmosphere, lakes, rivers, sea, and others. All of them have been made possible by the work of human minds, which we should celebrate, but we should also recognize that all of these pieces of information are obtained through a variety of instruments, not through our sensory organs which give the primary inputs to our mind. We cannot directly sense the global warming or the global cooling as we do the head- or stomach-ache.

We need to be careful about a likely disconnection between what we can know of through the contemporary "edge-cut" technology and what we perceive through our sensory organs. In other words, it is important for us to have a good command of imagination that can connect what we sense and perceive with a variety of physical quantities obtained from various advanced instruments. Such wisdom is to be re-developed, I think.

In the case of nuclear bombing, many people have come to know about the devastating consequence through the tragic stories disclosed by the people in Hiroshima and Nagasaki who happened to experience nuclear bombing some 65 years ago. Their experience has been passed on from them to the next generation to the following generations by story-telling, by the essays, and also by the exhibitions. The environmental issues including global warming seemingly caused by too much use of fossil fuels have not yet come to a stage comparative to the case of nuclear bombing. The fact that the rate of fossil-fuel use is still increasing proves the state of our mind that has not yet reached at a point similar to the nuclear-bomb tragedy.

Nevertheless, more and more trials aiming at environmental solutions are emerging as the reflection of the trend that more people have become aware of global environmental issues. It is not bad in a sense, but it is not good at all if they are still solely based on the old fashion of science and technology that realized not only the nuclear bombs but also our so-far developed societies. The environmental technology to be developed in the coming future should be based upon the rational science and philosophy.

Let me raise a simple example as analogy to make clear the point discussed so far. Suppose a situation that we think about what the ideal round shape is. There are many round shapes in our real world, the nature. To grasp the essence of its geometry, we need to know one of the very special irrational numbers, "π (=3.14159….)". More you understand what π is, more deeply you grasp what the essence of ideal round shape is. In a similar manner to this, if we are serious in having a better and deeper understanding of the energy and environmental issues and in finding their reasonable and sound solutions, it is necessary for us to have the appropriate scientific concept and make its full use. Such a concept in science associated with so-called energy and environmental issues parallel to the concept of "π" in geometry is, I believe, the concept of exergy.

2.2 Review of Fundamental Concepts: Mass, Energy, Entropy, and Exergy

As shown in Fig. 2.1a, the Sun always irradiates the Earth. The electromagnetic waves emitted by the Sun, traveling through the Universe deliver the solar energy whose average rate is 338 W/m^2 at the Earth surface, while at the same time the same rate of energy, 338 W/m^2, is emitted by the Earth into the Universe by thermal radiation. In due course, as mentioned earlier in this chapter, the average global temperature is maintained at around 15 °C.

Let us suppose a water tank as shown in Fig. 2.1b to strengthen our understanding of energy flows in and out the Earth. Some amount of water is assumed to be flowing into the tank from a faucet above the top, while at the same time exactly the same amount of water flowing out from the other faucet at the bottom. Thus, the water level of the tank remains unchanged. This is an analogy to the average global temperature remaining unchanged at 15 °C with the inflow and outflow of radiant energy through the atmosphere. If the rate at which the water flows into the tank is 1.5 L/s, the rate at which water flows out is also 1.5 L/s unless otherwise the water level must change. The same is true in the case of the Earth. If the average rate at which radiant energy flowing in from the Sun is 338 W/m^2, which is one-fourth of 1353 W/m^2 due to the ratio of a flat circular area to a spherical area, radiant energy flowing out to the Universe has to be at the same rate as 338 W/m^2.

The law of mass conservation applies to the water tank and the law of energy conservation applies to the Earth. Let us go a little further and ask ourselves the next question: isn't there any difference between "flowing in" and "flowing out"? If the answer is "No", water may be allowed to flow from the bottom to the top. This sounds very strange to our minds, because we know that such a phenomenon never happens spontaneously in the nature. But we should recognize that this is not against the law of mass conservation at all.

The same applies to the energy transfer by radiation. The wavelengths of thermal radiation emitted by the Sun are shorter than those of thermal radiation outgoing from the Earth into the Universe. The former is called solar radiation and the latter is long-wavelength thermal radiation. It does not matter if the Earth is irradiated by the long-wavelength thermal radiation coming from the Universe instead of the Sun, if the energy delivered by thermal radiation alone is the most important. But we all think that this sounds strange, because we are, though quite unconsciously, aware of the fact that radiation never changes its wavelength spontaneously from long to short, or its frequency from small to large. In order to clarify what can happen and what not in the nature, it is necessary to make the full use of entropy and exergy concepts, in addition to the concepts of energy and matter, both to be conserved.

Exergy is, in short, the ability of energy held by the assembly of atoms and molecules of matter or those atoms and molecules themselves to disperse into their environmental space. Once the dispersion starts taking place, the ability of energy to disperse gradually decreases in comparison to that in the moment before the

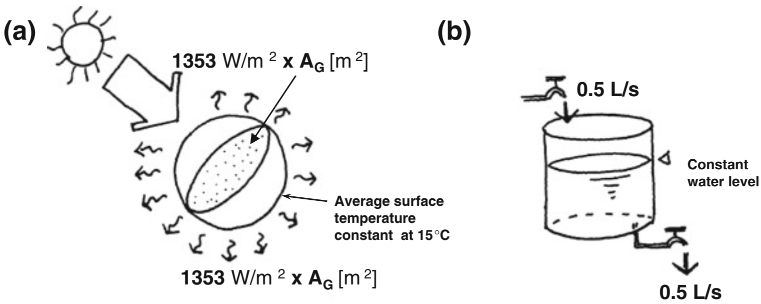

Fig. 2.1 **a** The reason why the global environmental temperature is kept almost constant at 15 °C is that the rate of solar energy coming onto the Earth (1353 × A_G) is always equal to that of thermal radiant energy going out to the Universe. The value of 1353 is the incoming rate of solar energy received by a surface of 1 m^2 normal to the solar ray and A_G is the largest sectional area of the Earth. **b** Supposing that there is a water tank and if the inflow and the outflow of water equals to each other at 0.5 L/s, the water level remains unchanged. The phenomena **a** and **b** are in exact similarity to each other with respect to energy conservation and mass conservation

dispersion started. The difference in the amount of exergy between before and after dispersion is "exergy consumption". The exergy concept quantifies explicitly what the consumption is.

The concept of entropy, which is in the position parallel to the concept of energy, quantifies how much of dispersion is held by an amount of energy and matter. The concept of entropy has been sometimes explained as the index of randomness or disorder. It is not wrong, if one is concerned about the similar concept with the same name in the information theory, which was very likely to be coined by the statistical implication of the entropy concept looking into the possible states of molecules with each of different potential and kinetic energy levels. But it is more important, from a holistic viewpoint, to grasp the essence of the entropy concept to be the quantity of dispersion in relation to energy and matter. In this regard, the concept of entropy may be considered to be "waste heat", which means the used heat to be dumped or "waste matter", which means the used matter to be dumped, in contrast to the concept of exergy as "resource" of energy or "resource" of matter.

As exergy is consumed, entropy is necessarily generated. The amount of exergy consumed is exactly proportional to that of entropy generated. A portion of "resource" is consumed by a system to do work as its objective while at the same time the "waste heat" or "waste matter" is inevitably generated and thereby they must be discarded into the environmental space of the system. The disposition of waste makes a space available within the system body to feed on newly the "resource" again for the next cycle.

We can observe such a process quite easily in a variety of systems from home electronic appliances such as personal computers and TV sets to the human body as a biological system. Replacing "resource" with "exergy" and "waste heat" and "waste matter" with "entropy" and observe how such systems work. Such observation will hopefully give you a bit of better understanding of these two concepts.

2.3 Viewpoint of Exergy-Entropy Process

Let us describe the global environmental system qualitatively with the concepts of exergy and entropy to confirm our understanding so far in this chapter. The electromagnetic waves coming from the Sun to the Earth delivers energy together with a lot of exergy, while at the same time the electromagnetic waves emitted by the Earth into the Universe gives off a large amount of entropy, most of which is the generated entropy due to the exergy consumption for all of the meteorological and biological phenomena taking place on the Earth surface where we live.

Mass and energy are conserved, exergy is consumed, and the corresponding entropy is generated proportionally, and finally the generated entropy is discarded. So the process continues. It may be harder to imagine the entropy disposal by radiation from the Earth than to imagine the exergy supply by solar radiation. The reason for this is that the inflow of solar radiation to the Earth can be sensed and perceived directly by us humans at the bottom of atmosphere, for example when walking outdoors or staying near sunlit windows during daytime on sunny days, but the outflow of long-wavelength thermal radiation from the Earth cannot be sensed and perceived directly by us. Nevertheless, we must admit that the entropy disposal from the Earth is the fact. This is because the entropy as a physical quantity contained by a lump of matter, here in this case the atmospheric air near the ground, has such a characteristic that it is a function of temperature whose increase results in its increase and also a function of pressure whose decrease results in its increase.

As mentioned earlier, the average atmospheric temperature near the ground surface of the Earth is almost constant at 15 °C. This implies that the entropy contained by the atmospheric air near the ground is constant. The average atmospheric pressure is also almost constant at 1013 hPa near the ground surface, though there are high and low pressures over the Earth surface. Recognizing these facts of constant atmospheric temperature and pressure and also the fact that any meteorological and biological phenomena can occur due to the consumption of solar exergy, we must conclude that the generated entropy due to exergy consumption at the Earth surface is endlessly discarded into the Universe.

Such qualitative investigation with an example of the global environmental system let us recognize that any system works as it feeds on exergy, its portion is consumed while at the same time the corresponding entropy is generated, and finally the generated entropy is discarded. This fundamental four-step cycle is called "exergy-entropy process". Table 2.1 summarizes this exergy-entropy process with an abstract explanation of each of four steps.

Figure 2.2 shows a numerical example of exergy-entropy process to be seen in the global environmental system which sustains its whole meteorological phenomena and biological activities while at the same time maintaining the annual average temperature at around 15 °C [11, 12]. The upper diagram shows the exergy supply and consumption; the lower the entropy generation and disposal.

Table 2.1 Exergy-entropy process consisting of four fundamental steps for a system to continue its work in cyclic operation

1. Exergy supply	To feed on energy or matter which has an ability to disperse
2. Exergy consumption	To disperse a portion of the supplied energy or matter inside the system to do work
3. Entropy generation	To generate an amount of entropy proportional to the amount of exergy consumed, due to the dispersion of supplied energy or matter
4. Entropy disposal	To dispose of the generated entropy into the environmental space from the system to let its temperature, pressure, and others, the quantities of state, at their necessary levels so that the process can return to the first step, exergy supply

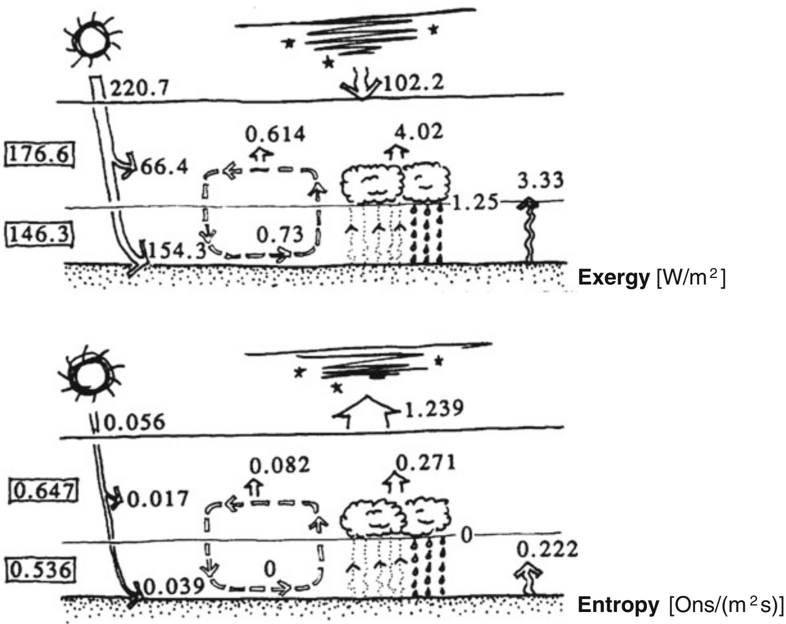

Fig. 2.2 Exergy-entropy process of the global environmental system. The upper diagram shows the rates of exergy supply and consumption; the lower the rates of entropy generation and disposal. The unit of exergy is W/m^2 and that of entropy is Ons/(m^{2}s). The figures in the squares indicate the exergy consumption rates in the upper diagram and the entropy generation rates in the lower diagram. Meteorological and biological phenomena occurring within the atmosphere are all given by the consumption of solar exergy and cool radiant exergy from the Universe. The generated entropy due to this exergy consumption, the difference in entropy flows between incoming and outgoing at the uppermost boundary of the atmosphere, is discarded into the Universe by long-wavelength thermal radiation

The global environmental system receives 221 W/m^2 of solar exergy while at the same time 102 W/m^2 of “cool” exergy from the Universe. The Sun and the Universe are hot and cold sources, respectively. Solar exergy, the ability of short-wavelength radiant energy to disperse, is consumed to make plants perform the photosynthesis, the retinal cells of our eyes be excited, and others. Finally to raise the temperature of various substances including the surface layer of the ground and the atmospheric air. ‘Cool’ radiant exergy available from the Universe is the ability of very low-temperature radiation filled in the Universe to lower the temperature of matter within the atmosphere.

In thermal exergy, there are two types of exergy: one is “warm” exergy and the other “cool” exergy as just raised above. On the one hand, the ability of energy contained by a lump of matter to disperse into its environmental space is called “warm” exergy, while on the other hand, the lack of thermal energy contained by a lump of matter compared to its environmental space, which causes the dispersion of energy from the environment to the matter in question, is called “cool” exergy. The fundamentals of warm and cool exergies are discussed in Chap. 4.

The exergy consumption in the global environmental system is 323 W/m^2; the sum of solar exergy and cool radiant exergy from the Universe. This consumption realizes the meteorological phenomena, mainly the air and water circulation within the atmosphere and the ocean, and various biological activities including us humans.

Let us move onto the lower diagram. The entropy is flowing out into the Universe at the rate of 1.239 Ons/(m^{2}s).[1] The entropy coming onto the global environmental system from the Sun is 0.056 Ons/(m^{2}s), which is very small due to its concentration of short-wavelength radiation compared to the outgoing entropy with scattered long-wavelength radiation. Their difference, namely 1.18 Ons/(m^{2}s) (=1.239−0.056), is the rate of entropy generated within the global environmental system due both to the consumption of solar exergy and the cool radiant exergy from the Universe. Meteorological phenomena within the atmosphere and the ocean and all of the biological activities including us humans as one of the biological systems are realized at the entropy generation rate of 1.18 Ons/(m^{2}s).

We humans come up with a variety of products, large and small, such as buildings, automobiles, airplanes, electric power plants, computers, and home-electronic appliances. All of them necessitate exergy supply and consumption for both production and operation. The exergy for these purposes comes from fossil fuels and condensed uranium. The amount of entropy due to this exergy consumption is not

[1] The unit of entropy “Ons” is the abbreviation of “Onnes”, which is equivalent to Joule (J) divided by Kelvin (K). This unit, Onnes, comes from the name of a scientist, H. K. Onnes, who was active in the second half of nineteenth century and contributed to the development of thermal physics, especially very low-temperature physics [7, 8]. The unit of “Onnes” has hardly been used in the textbooks of thermodynamics, but to the unit of such important concept of entropy the unique name should be given so that here in this book we use “Onnes” for the entropy concept. This idea is according to I. Oshida (1914–1987).

included in the entropy flowing out from the Earth at 1.239 Ons/(m^2s), since it is not originated from the solar exergy given by the present activity of the Sun.

The average rate of entropy generation over a unit surface area of the Earth due to fossil-fuel exergy consumption by contemporary global human societies is extremely small, less than 0.01 % of 1.239 Ons/(m^2s), the spontaneous entropy generation rate in the nature. But, locally, such as in Tokyo and Yokohama areas, this average rate has reached 0.12 Ons/(m^2s), 10 % of the outgoing entropy, 1.239 Ons/(m^2s). The global environmental issue has come up to the reach of our consciousness due to the fact that the generated entropy has reached the rate comparable to the order of the generated entropy due to the given natural exergy-entropy process.

Our way of living especially in the urban areas is made possible by an intense rate of exergy consumption, originated from fossil-fuels and condensed uranium. A sudden reduction of the exergy consumption rate in our society is analogous to stepping the brake pedal of a car running at extremely high speed on freeway. It is very dangerous because the car can easily slip even if the road surface is not wet. In such a condition of very high speed, the first action that we should take is to use the motor-brake so that the car can slow down gradually and reach a safe speed. It is vitally important for us to develop a kind of smart technology requiring less exergy consumption rate, which is analogous to driving a car with a safe speed. To do so, it is necessary to have a philosophical foundation.

Figure 2.3 shows an image of moderate exergy consumption rate, with which we should be able to enjoy fully the way of life, together with too small and too large exergy consumption rates. On the one hand, if you are asked to keep riding on a bicycle with a very low speed, it would be very difficult to balance your body without stepping on the ground, while on the other hand, if you are asked to keep riding with a very high speed, it would also be difficult to balance your body so as not to fall down and hit yourself on the ground.

With a moderate speed, you can enjoy riding on the bicycle. The moderate speed enables you to enjoy feeling the breeze and looking at the surrounding scenes passing by. To such bicycle riding, we can find a similarity for our futuristic way of life. To help solve energy and environmental issues, it is important, I think, to have such an image of moderate speed providing us with a state of well-being.

2.4 Circulation of Atmospheric Air and Water

Average atmospheric temperature near the ground surface of the global environmental system, from the Arctic to the Antarctic and also throughout one year, is about 15 °C. The corresponding temperature in the case of Venus is about 500 °C; and it is about −60 °C in the case of Mars. Such differences occur because Venus is closer to the Sun than the Earth and Mars is farther away from the Sun than the Earth.

The Earth is really in a good position relative to the Sun in the Universe; it is neither too close to nor too far away from the Sun. Any biological systems

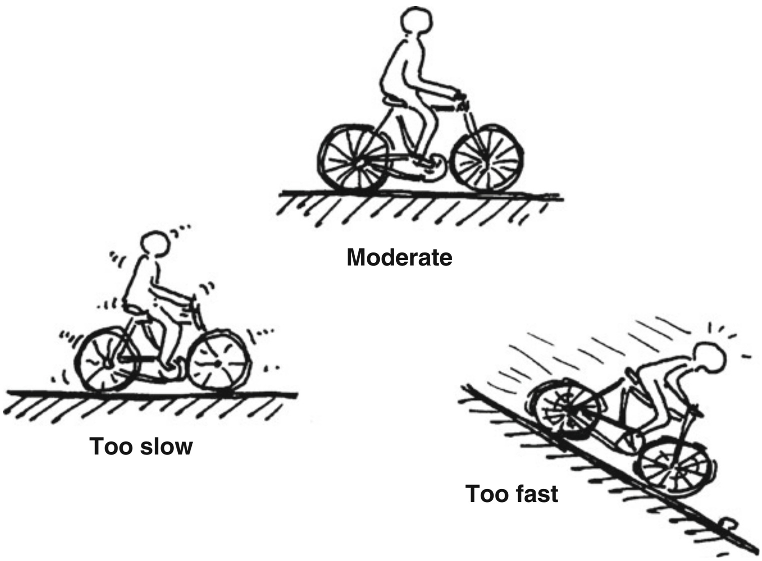

Fig. 2.3 If you are asked to keep riding on a bicycle with a very slow speed, it would be very difficult to balance your body in order not to step on the ground. On the other hand, if you are asked to keep riding with very fast speed, it would also be difficult or rather very dangerous to balance in order not to fall down and hit yourself on the ground. With a moderate speed, you can enjoy riding on the bicycle. The moderate speed enables you to enjoy the breeze and the scene passing by. The same applies to our life that requires a moderate rate of exergy consumption

including us, human-body system, contain a lot of water, which weighs more than 65 % of their body mass. Under the condition of the temperature of 15 °C with the pressure of 1013 hPa, the water can exist either in the state of liquid or in the state of vapor. This enables all biological creatures on the Earth to live.

The temperature of 500 °C on Venus can be realized only with ninety-time higher pressure than our atmospheric pressure, 1013 hPa; in this condition, there exists almost no water, while on Mars, the water with its temperature of −60 °C can exist in the state only of solid despite of any pressure conditions. All of biological systems live by feeding on foods including liquid water, consuming them and disposing of the wastes into their environmental space. Such physiological function cannot work at all under the condition of either 500 °C or −60 °C.

In what follows, let us discuss first the relative position and size of the Earth to the Sun, and then why the global environmental temperature, the atmospheric temperature near the ground surface, is realized to be at around 15 °C.

2.4.1 Understanding the Relative Size of the Earth

The diameter of the Earth is 1.27×10^7 m, the distance between the Sun and the Earth is 1.49×10^{11} m, and the diameter of the Sun is 1.39×10^9 m.[2] These large figures hardly enable us to imagine the relative position and sizes of the Sun and the Earth. Let us assume that the Earth is the size of a tennis ball, whose diameter is about 65 mm. Then, the diameter of the Sun relative to a scaled-down-model Earth becomes 7.1 m, equivalent to the height of a two-story detached house, and the distance between the Sun and the Earth becomes 765 m, a 10 min walking distance.

Imagine then a situation watching the Earth from the position of the Sun. A tennis ball located at a point of 765 m away must look nothing. This implies that most of the solar radiation scatters away into the universal space. Imagine next the other situation watching the Sun from the Earth; this is what we experience in reality. The Sun, almost equivalent to the appearance of a detached house that we see from a point 765 m away looks quite small. Nevertheless, the intensity of solar radiation that we sense on a day with fine weather is quite strong. Therefore, we must recognize how intense the radiation emitted by the Sun is.

The electromagnetic-wave radiation from the Sun is available due to the reaction of nuclear fusion occurring inside the Sun, which is realized under the condition of very high temperature and high pressure brought by huge gravitational force due to the huge mass of the Sun.

The surface temperature of the Sun is estimated to be 5700 °C according to its spectral characteristics of the emitted radiation. As mentioned above, the distance between the Sun and the Earth is large and the Earth looks almost a faintest circle so that the radiation reaching just outside the upper atmosphere of the Earth is very directional, even though the radiation emitted by the Sun is not directional.

According to what has been found by quantum mechanics, light has the characteristics both of wave and of particle. Let us suppose that the radiation traveling through the Universe to the Earth consists of a huge number of light particles. They are almost in parallel to each other. This results in the solar exergy-to-energy ratio being large. In fact, the ratio is 0.93 for extraterrestrial solar radiation. Chapter 4 discusses what the solar exergy is a little more in detail for the purpose of application to built environment.

The thickness of the atmosphere surrounding the Earth surface is about 30 km. In the case of a tennis-ball-sized model Earth having the diameter of 65 mm, the corresponding thickness of the atmosphere is 0.18 mm. Let us imagine drawing a circle with its diameter of 65 mm on a sheet of paper using a pencil of 0.2 mm diameter. The circular trace having the width of 0.2 mm is larger than the thickness of the model Earth, 0.18 mm. We come to recognize that the atmosphere of

[2] Those interested in how these figures can be obtained are welcome to read a column at the end of this chapter.

the Earth is extremely thin, though what we can sense by our sensory organs is rather opposite.

Let us add a couple of figures obtained from similar calculation to the above. The average depth of the hard shell above the liquid mantle is equivalent to 0.05–0.25 mm, and the depth of sea water, whose surface covers 70 % of the total Earth surface is equivalent to 0.019 mm in the model Earth of 65 mm diameter. Here we can have an image of the Earth having the overall thin moist-air layer, under which there is very thin hard shell, two-third of which is slightly concaved and covered by a thin film of liquid water. Such a globe is the Earth.

2.4.2 Estimation of Average Atmospheric Temperature Near the Ground Surface

We are aware of the fact that the Earth is turning around the Sun with an ecliptic orbit with the ratio of the shorter diameter to the longer being only 0.9998, that is very close to a true circle. The Earth is rotating around its center for 365.24 times a year and also turning around the Sun once a year. The average rate of energy and entropy delivered by solar radiation to just above the upper atmosphere can be assumed to be constant at 1353 J for a one-square-meter surface area normal to the direction of the Sun for each one second. We call it 1353 W/m^2. Its corresponding entropy is 0.3 Ons/(m^2s).

The diameter of the Earth measured between the North and South poles is slightly shorter than the diameter measured along the equator because of the rotation around the North–South axis, but we can again assume that the section is also a true circle. Therefore, the average rate of energy delivered by solar radiation over the upper-boundary of the atmosphere is, as already shown in Fig. 2.1a, 338 W/m^2, which is one-fourth of 1353 W/m^2 due to the ratio of surface area of a circle to that of a sphere.

According to the observation of incoming and outgoing solar radiation over the Earth surface, the average solar reflectance of the Earth is about 0.3. In other words, 70 % of the incoming solar radiation, 237 W/m^2 (=0.7 × 338 W/m^2), is always absorbed by the atmosphere and the ground; its corresponding exergy value is 221 W/m^2 (=0.93 × 237 W/m^2) as shown in Fig. 2.2.

(a) **A simplified-model Earth without atmosphere** Since the atmospheric air is very thin as mentioned above, let us first neglect the effect of atmosphere. Solar energy absorbed at the Earth surface is split into two parts of outgoing heat: one is outgoing long-wavelength radiation whose amount is determined by the surface temperature and the other is flowing into Earth shell by conduction. Since we are assuming no atmosphere, there is no convection.

As mentioned in the previous Sect. 2.4.1, the Earth shell is as thin as the atmosphere so that a certain amount of geothermal energy might be flowing up to the ground surface from the core of the Earth. The internal temperature of the ground of the Earth in reality increases as we go deeper at the gradient of about 1 °C each 25 m according to the measured result of underground temperature [14]. Nevertheless, the temperature at three meter deep below the ground surface in a certain region is almost the same as annual average air temperature in that region. Therefore, let us assume that the boundary surface at 3 m deep from the ground surface as adiabatic for the present calculation. This imaginary boundary splits the upper thin layer whose temperature is influenced by the local weather conditions from the lower layer whose temperature is influenced by the heat transferred from the deep core Earth.

The core of the Earth, from the center to one half of the radius, which corresponds to 16 mm of a tennis-ball-sized model Earth, is believed to consist mostly of nickel and iron. Its internal part, which corresponds to 6 mm from the center of the model Earth, is considered to be in the state of solid and the rest, up to 16 mm in liquid state. The temperature of the liquid core is believed to be in the order of 4000 °C at the boundary and 6000–7000 °C at the center due to nuclear fission reactions [4].

Above the core is the layer called "mantle", most of which is in the state of liquid, and further above it there is the solid shell corresponding to the thickness of 0.05 to 0.25 mm in the model Earth, on which we live. We can extend our imagination that we humans live on the surface of very thin plates and at the bottom of a scant layer of atmosphere.

Let us go back to the estimation of average atmospheric temperature near the ground surface. According to what we have discussed above, we can assume that the solid shell is a kind of adiabatic layer, through which there is no heat transfer, as long as we are focusing on the average annual ground-surface temperature. As in the case of a water tank whose water level remains unchanged as long as the inflow rate to the tank is just equal to the outflow rate, the global surface temperature remains unchanged as long as the inflow rate of energy originating from the Sun is just equal to the outflow rate of energy by thermal radiation into the Universe from the Earth. This is expressed by the following equation assuming the shell of the Earth to be adiabatic.

$$(1-\rho)I = \sigma T_g^4 \tag{2.1}$$

The left-hand side of this equation is the rate at which energy brought by short-wavelength radiation coming from the Sun is absorbed, and the right-hand side the rate of long-wavelength thermal radiation emitted by the Earth toward the Universe. The formula used for the right-hand side of this equation is according to the law that the thermal energy emission rate by radiation is proportional with the constant value, σ, of 5.67×10^{-8} W/(m^2 K^4), to the fourth power of absolute temperature of the radiant source[3], which in this case the Earth surface.

[3] This relationship is called Stephan-Boltzmann's law commemorating the experimental finding owing to Stephan and its theoretical foundation to Boltzmann. The proportional constant denoted by the symbol, σ, is called Stephan-Boltzmann constant.

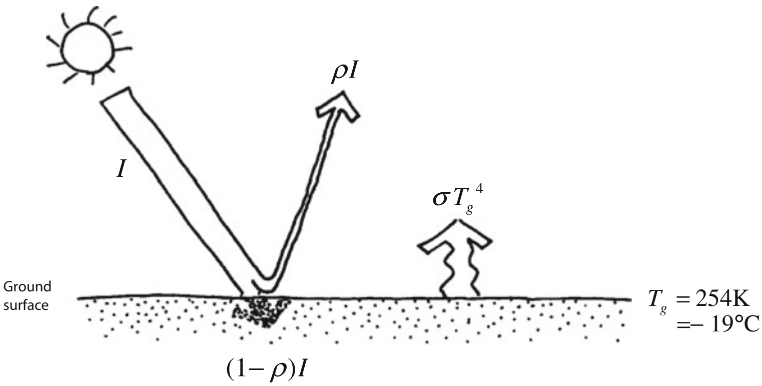

Fig. 2.4 Energy balance at the ground surface assuming no atmosphere. Substituting the values of the ground-surface reflectance and the average rate of energy incident on the ground surface into Eq. (2.1), we find the ground-surface temperature to be 254 K(−19 °C)

The unknown variable in Eq. (2.1) is only the average ground-surface temperature of the Earth, T_g, since we can assume that the overall solar reflectance, ρ, of the Earth is 0.3, and the average rate of solar energy incident upon the Earth surface, I, is 338 W/m^2 as already mentioned in the previous subsection. Therefore, we can easily calculate the value of T_g^4 and then its quadruple-root. The result is 254 K (−19 °C). It is much lower than the value of the global temperature to be expected, 15 °C. Figure 2.4 shows schematically the relationship expressed by Eq. (2.1) and the results calculated.

(b) **A simplified-model Earth with atmosphere but no air and water circulation** The result above, which is totally different from the actual global environmental temperature, is due to the negligence of atmosphere. Therefore, let us next assume that there is a thin-film like atmospheric roof whose optical properties are as follows: it absorbs no short-wavelength solar radiation, namely totally transparent, but completely the long-wavelength thermal radiation, namely totally black. The ground-surface reflectance to the solar radiation is assumed to be the same as before, 0.3.

The atmospheric roof is surrounded both by the Universe and the ground surface so that it absorbs the long-wavelength thermal radiation coming from both the Universe and the ground surface. The amount of the long-wavelength thermal radiation from the Universe is so tiny, almost nothing according to the fourth-power law mentioned above, since the temperature of the Universe is only 3 K (= −270 °C)[4], while on the other hand, the ground surface is in the order of 300 K.

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[4] This was made clear by the advancement of the contemporary astrophysics [15]. In the year of 1964, A. Penzias and R. W. Wilson found that the Universe is filled with radiation at the wavelength of 1 mm and speculated that it must be the radiation from a black body whose temperature is around 3 K. Later in 1990s, G. Smoot, S. Mather et al. made a series of very accurate analysis with the very precise measurement using an artificial satellite called COBE and

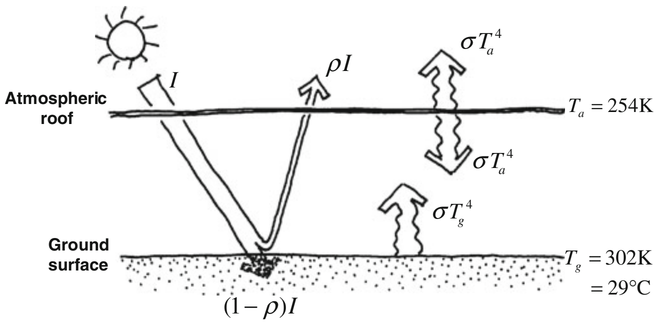


Fig. 2.5 Energy balance of the atmospheric roof and the ground surface. The atmospheric roof is assumed to be completely transparent to solar radiation and completely black against long-wavelength thermal radiation. The ground-surface temperature turns out to be 29 °C, much higher than 15 °C to be expected

For this reason, the atmospheric roof can be regarded a medium that absorbs only the long-wavelength thermal radiation from the ground surface and emits the long-wavelength thermal radiation at the rate corresponding to the roof temperature toward both the Universe and the ground surface.

The ground surface absorbs 70 % of incoming solar energy and the whole of long-wavelength thermal radiation emitted downwards by the atmospheric roof and it emits the long-wavelength thermal radiation upwards to the lower surface of atmospheric roof.

What has been explained so far above can be reduced to a compact expression using the following two equations for the atmospheric roof and the ground surface, respectively.

$$\sigma T_g^4 = \sigma T_a^4 + \sigma T_a^4 \tag{2.2}$$

$$(1 - \rho)I + \sigma T_a^4 = \sigma T_g^4 \tag{2.3}$$

The two symbols, T_a and T_g, denoting the absolute temperature of the atmospheric temperature and of the ground surface, respectively, are two unknowns in the Eqs. (2.2) and (2.3) so that these equations can be solved with respect to the values of T_a and T_g. The results are $.T_a = 254\text{K}$.and $.T_g = 302\text{K}$.; in the scale of Celsius temperature, the atmospheric roof is −19 °C and the ground surface is 29 °C. The ground-surface temperature is higher than the case assuming no atmospheric roof described above, but this time it is 14 °C higher than the value, 15 °C to be expected. Figure 2.5 summarizes the above results together with the relationships expressed by Eqs. (2.2) and (2.3).

(Footnote 4 continued)
they found that the spectral distribution of the radiation filled in the Universe is exactly that of black body at the temperature of 2.725 K.

(c) **A simplified-model Earth with atmospheric air and water circulation** The above result of 29 °C as the average ground-surface temperature is too high, but there are some local areas with such high annual average temperature. These are desert regions relatively close to the equator, whose characteristics are little water available and few plant and animals living.

The neglect of evaporation and condensation of water together with convection of the atmospheric air, which we are familiar with, in setting up Eqs. (2.2) and (2.3) must have resulted in the estimated temperature to be much higher than that to be expected. In the actual atmosphere, the air flows between the high and the low pressures, namely the wind, and the liquid water evaporates at the ground, the sea, and the river surfaces due to their temperature rise for solar energy absorption, and the resultant water vapor disperses into the atmospheric air.

The upward moist-air current causes the emergence of low-pressure and the water vapor within the upward air current condenses again into liquid water, which thereby forms clouds. The air that has given up the water vapor still goes up, but it contracts gradually due to the decrease in temperature and hence its density becomes large so that it starts to flow downward as dry-air current and it causes the high pressure. The liquid water comes back again as rain from the clouds to the ground surface, the sea, and the river surface. So the water circulates within the atmosphere.

Let us modify the above Eqs. (2.2) and (2.3) so that they include the thermal energy transfer by air and water circulation. Supposing that the rate of thermal energy transfer is denoted by symbol H, Eqs. (2.2) and (2.3) can be rewritten into the following equations, respectively.

$$\sigma T_g^4 + H = \sigma T_a^4 + \sigma T_a^4 \tag{2.4}$$

$$(1-\rho)I + \sigma T_a^4 = \sigma T_g^4 + H \tag{2.5}$$

On the one hand, the term H appearing in the left-hand side of Eq. (2.4) represents the thermal energy transferred to the atmospheric roof by convection together with the condensation of water vapor. On the other hand, the corresponding term H appearing in the right-hand side of Eq. (2.5) represents the thermal energy swept out from the ground by convection together with the evaporation of water.

These two equations cannot be solved by themselves, since there are three unknown variables, T_g, $T_{a,}$ and H. Therefore, let us substitute an expected value of the average ground-surface temperature, 288 K (=15 °C) to T_g and regard Eqs. (2.4) and (2.5) with two unknown variables, T_a and H. Then these equations can be solved and the result is 254 K (−19 °C) for T_a and 80 W/m^2 for H.

Figure 2.6 shows the result of this calculation together with the relationships expressed by Eqs. (2.4) and (2.5). The evaporation of liquid water and the condensation of water vapor together with the atmospheric-air circulation and the resultant falling down of liquid water as rain deliver about one-third of the thermal energy, which originated from the Sun. We now come to recognize that such atmospheric air and water circulation plays a crucial role for the air temperature near the ground surface to be 15 °C.

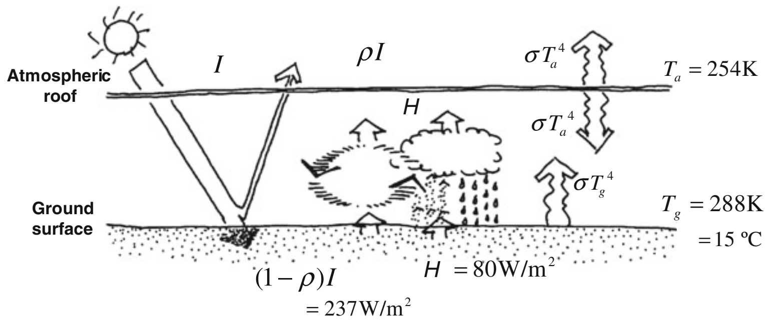


Fig. 2.6 Energy balance of the atmospheric roof and the ground surface with an assumption of the atmospheric air and water circulation, which delivers thermal energy at the rate of 80 W/m^2 from the ground to the atmospheric roof. This realizes the ground-surface temperature to be 15 °C

2.4.3 Dispersion and Separation of Water as the Working Fluid of Atmospheric Heat Pump

In the above discussion, we assumed that the atmospheric roof is completely transparent against solar radiation and is completely black against long-wavelength thermal radiation.

But the actual atmosphere does not behave so: some amount of solar radiation is absorbed by the atmosphere before it reaches the ground; and some amount of long-wavelength thermal radiation emitted by the ground surface transmits through the atmosphere. The energy balance taking such actual phenomena into consideration is shown in Fig. 2.7 [5, 9]. What we can read from this actual energy balance is as follows.

The rate of thermal energy emerged at the ground surface by the absorption of solar energy, 165 W/m^2, is about 50 % of solar energy incident upon the top of atmosphere and that within the atmosphere, 71 W/m^2, and is about 20 %. Their sum, 236 W/m^2, that is 70 % of the incident solar energy, fits the fact that the overall absorptance of the Earth is 0.7. These rates of thermal energy emerged play a role in increasing the ground surface and the atmospheric-air temperature.

The ground surface emits long-wavelength thermal radiation upwards at the rate of 391 W/m^2 (=371 + 20) and the atmospheric air emits it upwards at the rate of 216 W/m^2 and downwards at 327 W/m^2. The difference in energy transfer rate by long-wavelength thermal radiation between from the ground upwards and from the atmosphere downwards turns out to be 64 W/m^2 (=371 + 20−327) as the net energy transfer rate by thermal radiation toward the upper atmosphere from the ground.

The energy transfer rate by water evaporation both at the sea and at the ground surface is 78 W/m^2, and that by atmospheric-air convection is 23 W/m^2; their direction of net thermal energy delivery is also from the ground to the upper

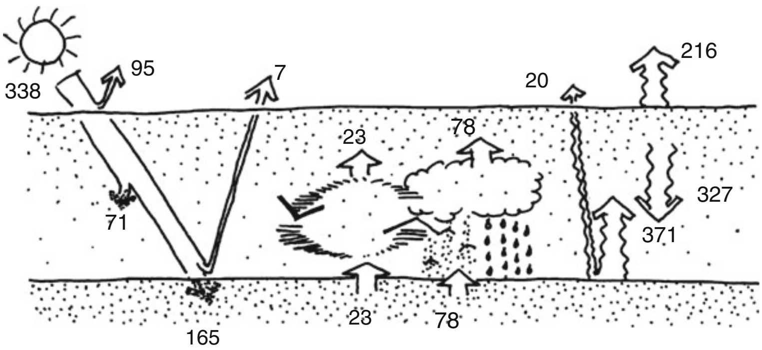


Fig. 2.7 Energy balance of the atmospheric roof and the ground surface. The figures represent the average over the Earth in the unit of W/m^2. The atmospheric air and the ground surface absorb and reflect solar radiation. There is the circulation of air and water delivering thermal energy from the ground to the upper atmosphere together with long-wavelength radiation emitted by the ground and absorbed by the atmosphere. The upper atmosphere emits long-wavelength radiation toward the ground and the Universe simultaneously

atmosphere. Their sum, 101 W/m^2 (=78 + 23), corresponds to thermal energy delivered at the rate of 80 W/m^2 obtained from the calculation made with Eqs. (2.4) and (2.5). We confirm that our rough estimation explained in the previous subsection was all right.

The amount of energy delivered by the water evaporation and condensation is 3.4 times (=78/23) larger than that by the atmospheric air itself. This fact proving the importance of water on the Earth surface to make its temperature remain unchanged at 15 °C lets us understand why the Earth we live on is called “the Aquatic Planet”.

Thermal energy received by the atmosphere due to solar energy absorption, atmospheric-air convection, water condensation forming clouds, and long-wavelength radiant energy absorption is summed up to be 543 W/m^2 (=71 + 23 + 78 + 371). Its portion, 327 W/m^2 (60 %) is emitted by long-wavelength thermal radiation toward the ground surface, and the rest, 216 W/m^2 (40 %) is emitted toward the Universe. The total of long-wavelength radiant energy emitted toward the Universe from the Earth turns out to be 236 W/m^2, since there is long-wavelength radiant energy of 20 W/m^2 emitted by the ground surface and transmitted through the atmospheric air. This transmission takes place mostly for the long-wavelength thermal radiation at the wavelength of 8 to 13 μm. This range of the wavelength with respect to the atmospheric air is often called “the Atmospheric Window”.

The total of long-wavelength radiant energy emitted, 236 W/m^2, equals the difference between the solar energy reaching just outside the Earth, 338 W/m^2, and the total of reflected solar energy, 102 W/m^2(=95 + 7). This confirms that the energy inflow balances with the energy outflow on the Earth based on the law of energy conservation.

Let us discuss further the water circulation on the Earth. As wind blows over our skin surface when sweating due to hot weather or after taking shower, then we feel cool. This is due to a sudden decrease of skin-surface temperature caused by the evaporation of water into the environmental space. The amount of thermal energy to be delivered by the evaporation of 1 kg of water whose temperature is 15 °C is 2450 kJ, that is 2450 J/g of latent heat and its corresponding entropy value is 8.5 Ons/g (=2450/(273.15 + 15)).

With the value of latent heat, we can estimate the rate of water evaporation that carries the thermal energy at the rate of 78 W/m^2. Since the unit W is equal to J/s, 78 W/m^2 is 78 $J/(m^2s)$ and the division of 78 $J/(m^2s)$ by the latent heat value of 2450 J/g gives us the rate of evaporation, 31.8 $mg/(m^2s)$. The evaporation takes place at a variety of places all over the Earth surface; the ground surface, the sea surface, the river surface, the surfaces of leaves of plants, the skin surfaces of animals including our human-body skin. Calculating the annual value of the water evaporation using the values above, it turns out to be about 1000 $kg/(m^2$ year) ($=31.8 \times 10^{-6} \times 3600 \times 24 \times 365$). This is just the same as annual precipitation observed in reality on the Earth.

As mentioned in the previous subsection, 70 % of the Earth surface is covered by sea water and the rest is naked Earth shell, continents and islands, on which land plants and land animals are living. Although much of the evaporation of water takes places at the sea surface, there is also some from the surfaces of rivers, lakes, wetlands, and also from the skin surfaces of land plants and land animals whose bodies are filled mainly with water. Such evaporation of water here and there accumulates up to the value of 1000 kg/m^2 for 1 year. This amount of water vapor comes back again as precipitation after it gives off 78 W/m^2 of thermal energy when it forms clouds by condensing into liquid water. So circulates the water on the Earth.

The evaporation of water is, in other words, the mutual dispersion of water and atmospheric air and the condensation of water is the separation of water from the moist atmospheric air. Such dispersion and separation is the key to enable the global environmental system to keep its average temperature almost constant at 15 °C by performing the "exergy-entropy process" described in the Sect. 2.3.

The following four facts are the keys to realize the global environmental system working as exergy-entropy process.

First, the Earth is heavy enough to keep all molecules of air and water within the height of atmospheric layer over the Earth surface. If the Earth were much lighter, it must have given off the molecules of air and water dispersing into the Universe as the moon did before.

Second, the Earth is not too heavy so that the water on the Earth can exist either in the state of solid (ice), liquid (so-called water), or gas (water vapor). On the one hand, the density of liquid water, i.e., the mass contained by a unit volume, is much larger than that of atmospheric air so that liquid water can sink to the bottom of the atmospheric-air sea, while on the other hand, water vapor is dilute enough compared to the atmospheric air so that it can float up in the middle of the sea of atmospheric-air layer until it condenses into liquid water again.

Third, the Earth is neither too far away from nor too close to the Sun so as to receive solar exergy at the rate of 221 W/m^2, an appropriate rate that is enough to make the liquid water evaporate at an optimum rate for realizing the average global environmental temperature at around 15 °C as shown in Fig. 2.6.

Fourth, melting and evaporating temperature levels of water are much higher than those of similar kinds of molecules [2, 13]. Each molecule of water has a special form that one of the two hydrogen atoms does not exist on the straight line stretching out between the other hydrogen atom and the oxygen atom. Such a folded form brings about the external side of the oxygen atom being a little negative in the electric charge and those of the two hydrogen atoms a little positive. Such positive–negative peculiarity that is called hydrogen bond does not exist in the case of the molecules having a similar form with two hydrogen atoms and sulfur and others in between.[5]

High evaporating temperature implies that water molecules can deliver a lot of thermal energy as they turn themselves from the state of liquid to that of vapor. Such characteristic of water makes the dispersion and separation of water within the atmosphere very effective in delivering thermal energy as shown in Figs. 2.6 and 2.7.

The combination of evaporation and condensation of water taking place within the atmospheric layer, which is crucial in realizing the average temperature of 15 °C in the above discussion, is in fact the same as what is happening inside heat pumps including refrigerators being used in our society for a variety of purposes. In other words, we may regard the global environmental system as a huge heat pump system realized by the Nature.

The heat pumps in refrigerators and the air-conditioning units work by feeding on exergy from the electricity grids, consuming its portion to circulate the working fluid inside the closed space formed by a series of pipe works connecting a compressor, a heat exchanger for condensation, an expansion valve, and the other heat exchanger for evaporation. The working fluid produces "warm" exergy and "cool" exergy as it circulates being contracted at the compressor and being expanded at the expansion valve.

The expansion of the working fluid and its resultant thermal energy/entropy absorption in artificial heat pumps correspond to the evaporation of liquid water and its resultant thermal energy/entropy absorption at the Earth surface, while on the other hand, the compression of the working fluid and its resultant thermal energy/entropy emission in the heat pumps correspond to the condensation of water vapor and its resultant thermal energy/entropy emission into the upper atmosphere of the Earth.

The water within the atmospheric layer over the Earth surface is the working fluid, the atmospheric layer is the space corresponding to the internal space of

[5] Water denoted by the symbols in chemistry is H_2O. There are other molecules, in which the position of oxygen is replaced with sulfur, S, that is H_2S, Selenium, Se, that is H_2Se, Tellenium, Te, that is H_2Te. Their melting and evaporating temperatures levels are much lower than those of water.

artificial heat pumps, where the working fluid circulates, and the gravitational force of the Earth is equivalent to the strength of pipe works connecting a condenser, an evaporator, a compressor, and an expansion valve as a closed space with high pressure in one part and with low pressure in the other.

Inside such global environmental system working in a sustainable manner as a huge heat pump in the Nature, the built environment, in which we humans live, is realized.

2.5 Circulation of Matter Within the Biosphere

We discussed the "exergy-entropy process" of the Earth as a kind of heat engine in the previous subsection and thereby we have just come to recognize that the circulation of air and water is essential in keeping the average global environmental temperature at around 15 °C.

In fact, there is one other important circulation that we should keep in mind: that is the circulation of nutrients. In all ecosystems, either at large scale or at small scale, consisting of a variety of living creatures from microbes to plants to animals including us humans, the nutrients for respective members of the ecosystems always circulate, as so-called food chain, changing their chemical characteristics by a series of decomposing reactions from large-sized complex molecules to small-sized simple ones or composing from simple to complex.

Let us take a look at a typical ecosystem in general. First, plants perform photosynthesis process feeding on short-wavelength radiation from the Sun and also carbon-dioxide molecules from the surrounding air through their leaves, while at the same time, feeding on quite a good amount of liquid water together with minerals from their roots stretching out into the layer near the ground surface. Although there are a variety of products of photosynthesis, let us take the molecules of glucose as the primary product. They are used not only for the plants themselves to grow their bodies but also for the herbivores to feed on. Herbivores depend on plants and carnivores on herbivores and other carnivores. In short, all of living creatures are dependent on plant bodies and are connected as a chain.

Once the living creatures, whether they are plants or animals, end their life, their bodies made up with a variety of complex organic compounds start to decompose by eaten either by other animals or by microbes. Anyway, sooner or later, all of those bodies are finally decomposed into simple rudimentary molecules of life. The same applies to the organic wastes given off by living animals.

Those simple rudimentary molecules are solved in rain water and then absorbed again by the roots of plants. In this way, each individual animals and microbes connects with one to another as a member of the food chain and thereby all together form an ecosystem.

There are a variety of poisonous matters produced by plants and animals. Whether a certain poisonous matter is harmful or not depends on the kind of plants and animals; some animals as predator use poisons to hunt their prey effectively and also other animals use poisons to protect them so as not to be prey from their predator.

Beyond such poisonous matters naturally-developed, we humans have developed an ability either to make use of such matters which have become scarce in the course of natural history so that all living creatures have been able to develop or to synthesize matters which are alien and toxic to almost all of living creatures and hard to be decomposed within a short period of time within the ecosystems.

Their toxicity does not disappear because the animals cannot digest effectively so that it concentrates while being circulated. Such concentration through the prey-and-predator process could destroy a part of or a whole of the ecosystem. Therefore, such a technology which can inevitably produce artificial matters toxic to living creatures should not be adopted not only by local societies but also by global societies.

Figure 2.8 shows schematically the circulation of carbon atoms within the whole of land ecosystems on the Earth and Fig. 2.9 the corresponding average rate of chemical exergy produced by photosynthesis on the Earth surface of 1 m^2, which was estimated based on the figures of carbon mass given in Fig. 2.8.[6] The plants fix carbon atoms in the form of glucose by photosynthesis at the rate of 120 Pg(=10^{12} kg)/year by taking in carbon-dioxide molecules existing in the environmental space, as the primary material for photosynthesis, while at the same time discharge 60 Pg/year as the waste.

Chemical exergy produced by the plants as the form of glucose molecules is estimated to be 1.15 W/m^2 as shown in Fig. 2.9. Its half is consumed by the plants themselves for their life and the other half is absorbed and consumed by animals and microbes. Such a series of exergy consumption ends up with the emission of carbon-dioxide molecules, which has no exergy at all together with the emission of thermal entropy into the atmosphere. Carbon-dioxide molecules are again absorbed by plants as shown in Fig. 2.8; 115(=60 + 55) Pg/year out of 120 Pg/year to be fixed comes directly from the land ecosystem, to which the plants belong. So the circulation of carbon is performed within the ecosystem.

If the rate of chemical exergy production balances exactly that of chemical exergy consumption, then the chemical exergy storage does not emerge. But, over the long history of the Earth, some of the dead bodies of plants and animals, which happened to spin off from the circulations, mentioned above, were gradually piled up and covered by rocks and soils due to geological activity. That is fossil fuel on which our contemporary societies are highly dependent.

Looking carefully at Fig. 2.8 again, the cycle of carbon mass in the whole of land ecosystems is not closed: 0.6(=120−(60 + 55 + 4+0.4)) Pg/year of carbon atoms looks missing. Some of or all of them must remain under the ground and may form a portion of fossil-fuel resources many billion years later.

[6] Those interested in how to estimate "chemical" exergy values are welcome later to go to Sect. 5.6.

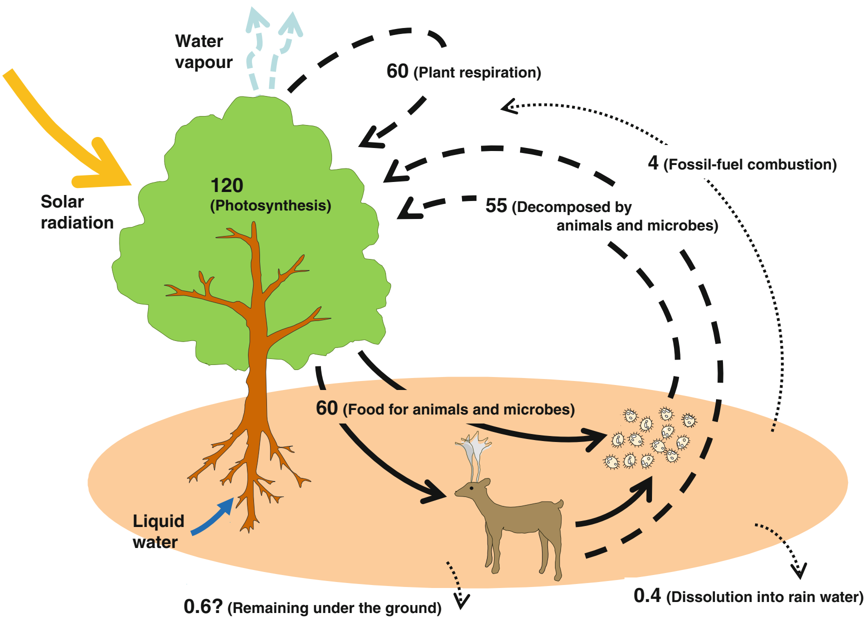


Fig. 2.8 Circulation of carbon atoms in mass rate by Pg (=10^{12} kg)/year within the whole of land ecosystems on the Earth (this figure was made by modifying a drawing originally prepared by I. Takahashi referring to the data given by NIES [6])

If we assume the rate of 1.15 W/m^2 mentioned above corresponds to 3 % of the solar exergy absorbed by the plant leaves, then we come to know that the plants absorb solar exergy at the rate of 38.3 W/m^2, which is about one-fourth of the solar exergy absorbed at the ground surface, which is 154.3 W/m^2 as shown in Fig. 2.2.

As will be described later in Sect. 3.9, the consumption of "wet" exergy contained by liquid water is also very important in parallel to solar exergy consumption for photosynthesis. That is the "wet" exergy contained by 99 % of the mass of liquid water absorbed by the plants from their roots, all of which is consumed to cool down their leaves. The rate of "wet" exergy contained by liquid water absorbed by the roots of plants, 0.1 W/m^2, reaches almost 17 % (=0.1/0.575 × 100) of the chemical exergy produced by photosynthesis.[7]

Figure 2.10 shows those values of chemical exergy rate in relations to photosynthesis together with the exergy rate values already shown in Fig. 2.2. The rate of 0.575 W/m^2 at which animals and microbes feed on from the plant bodies corresponds to 80 % of the kinetic exergy rate of 0.73 W/m^2 delivered by atmospheric air and also to 46 % of the potential exergy rate of liquid water at 1.25 W/m^2 and 19 % of "wet" exergy contained by all rain water, 3(=0.1 + 2.9) W/m^2.

[7] Its detail is described in Sect. 5.8.

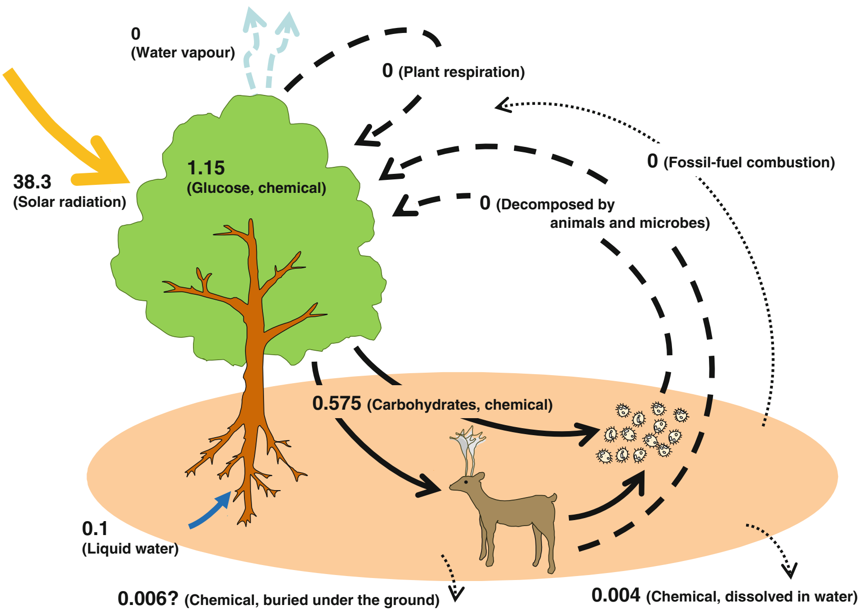


Fig. 2.9 Rate of chemical exergy produced by photosynthesis together with solar exergy and "wet" exergy absorbed by plants in the unit of W/m^2. A half of the produced exergy is consumed by the plants themselves and the other half by animals and microbes (this figure was made by modifying a drawing originally prepared by I. Takahashi referring to the data given by NIES [6])

These exergy values emerged in the respective cycle of carbon, atmospheric air, and water are in the same order of magnitude.

It is not hard for us to be conscious to the movement of atmospheric air as we can feel wind by our own skin surfaces and also to that of water as we can see clouds over the sky by our own eyes and get wet by rain, but it is hard to be conscious enough to the circulation of carbon, from plants to animals including us humans to microbes, and again to the plants within the land ecosystem. But with the above estimation of chemical exergy contained with carbon atoms in the form of glucose let us recognize the importance of carbon cycle.

Since the whole mass of matters concerned is necessarily conserved in a series of photosynthetic and decomposing activities within an ecosystem, it is essential for the ecosystem to keep feeding on, consuming the chemical exergy and disposing of the resultant entropy generated in order to sustain "nutrient" circulation within the ecosystem [3, 10, 16].

Once we have a little bit better view of how an ecosystem works with the exergy concept as mentioned above, environmental technology to be developed looking into the future should not be limited only in relation to flow of energy but also to the circulation of matter; that is to make a smart use of chemical exergy contained by organic waste matter to feed on those plants, animals, and microbes

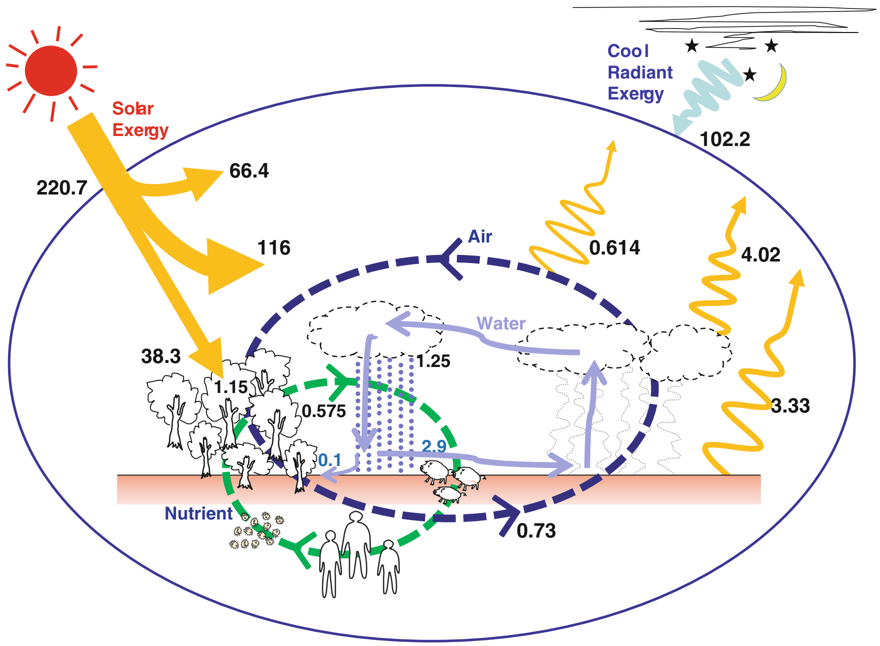


Fig. 2.10 Circulations of air, water, and nutrient within the global environmental system and their associated exergy rate in the unit of W/m^2. The chemical exergy produced by the consumption of solar exergy together with the disposal of generated entropy by cool radiant exergy available from the Universe drives the circulation of nutrient within the global environmental system and thereby realizes the sustainability

in the lower levels of the ecosystem. A composting system or an ecological toilette system treating with disposed matter within local communities to be described in Sect. 3.10 is a kind of such systems that we should also take a look at.

Column 2: Estimating the Sizes of the Earth and the Sun Together with their Distance

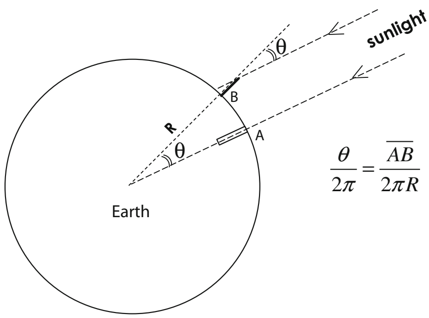
The sizes of the Earth and the Sun as well as the distance between them cannot be measured directly, but can be obtained from a rather simple series of calculation with the pieces of information available from a simple measurement even including the ones possible for us so that you are advised to do your own calculation, which assures you of having a clearer image of geometrical relationship between the Earth and the Sun.

First, suppose that you are standing at some point, A, on the Tropic of Cancer, whose latitude angle is 23.45°. The sunlight incident upon there at noon on the day of summer solstice, which is the longest day of the year, comes from the direction of zenith. In other words, the solar altitude is 90°. Therefore, if there is a vertically deep well, the sunlight can illuminate its bottom. Suppose next that you are at some other point, *B*, due north of point *A*, and if there is also a vertically deep well there, you will find that its bottom is not illuminated, but a portion of the side-wall is illuminated at noon on the day of summer solstice.

With these facts, we can develop an idea of the geometrical relationship that the Earth is a huge sphere and the Sun is so remote that the sunlight available at points *A* and *B* is parallel to each other. Then, if we measure both the distance between *A* and *B* and the shadow length of a vertical stick at *B*, the diameter of the Earth can be estimated.

This was first done by Eratosthenes, who lived 2300 years ago in Egypt. He had the figure of distance between Syene and Alexandria and also knew that at noon of summer solstice the bottom of a deep well in Syene was illuminated by sunlight, but not in Alexandria. Instead, the shadow length of a vertical stick in Alexandria was one-eighth of the vertical stick; this corresponds to 7.2° subtended at the top of the stick by the bottom of the stick and the edge of the shadow.

We can confirm where these two places are located on the map; Syene is now called Aswan and its latitude is 24.05°, very close to the Tropic of Cancer, and Alexandria is located in the north of Aswan, only 3° westward.



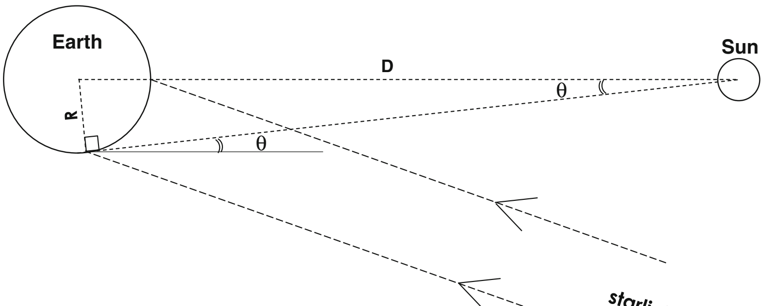
$$\frac{\theta}{2\pi} = \frac{\overline{AB}}{2\pi R} \Rightarrow R = \frac{\overline{AB}}{\theta}$$

The figure of distance between Syene and Alexandria that Eratosthenes knew was 5000 stadia, which was the ancient unit of length used in Egypt, equivalent to 158 or 185 m in SI unit. Since 7.2° is one-fiftieth of 360°, the circumference of the Earth turns out to be 250000 stadia. Then, the diameter of the Earth is estimated to be 79600 stadia, which is only 1.3 % smaller when assuming one stadia to be 158 m or 16 % larger when assuming one stadia to be 185 m than the diameter of the Earth known today, 12740 km. This is really a remarkable research result of geometrical science applied then.

The distance between the Earth and the Sun can be estimated in a similar way as follows. According to a series of astronomical observation having been done since the ancient time, we now know that the Earth is rotating around the Sun. Our ancestor came to know the following two things first: one is that the relative positions of the stars are always constant, although the stars that you can see up in the sky vault during night time vary with seasons of the year; the other is that the planets such as Venus and Mars change their positions relative to other stars on the sky vault occasionally in some complicated manner.

The fact that the relative positions of stars are always constant allows us to conceive that all of the stars are much farther away from the Earth than other planets and the Sun are. Assuming such characteristics together with the idea of the Earth rotating around its center, it is recognized that there emerges a slight difference in the angle subtended by a target star and the Sun according to the rotation of the Earth. That is a parallax. Since the parallax becomes the largest for a point on the equator, the measurement should be made there. The difference in angle values is taken between when the point is at sunrise, the solar altitude of 0° and when it is at noon, the solar altitude of 90°. During daytime, we cannot see any starlight directly because of intense daylight, but as mentioned above, we know that the relative positions of the stars over the sky vault are constant so that those angles are obtained from a combination of measurement and calculation.

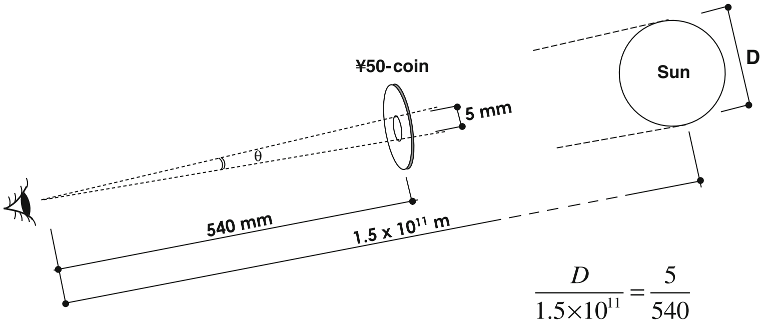
According to a sufficiently precise measurement, the parallax observed at the equator is 0.00243°, which is equal to 0.00004249 radian. The division of the radius of the Earth, 6370 km, by sine value for 0.00004249 radian brings us the distance of the Earth and the Sun to be 1.5×10^{11} m.



$$\sin\theta = \frac{R}{D} \;\Rightarrow\; D = \frac{R}{\sin\theta} \approx \frac{R}{\theta}$$

The distance between the Earth and the Sun can also be obtained from geometrical relationship between the Sun, the Venus, and the Earth. The maximum angle subtended by the Sun and the Venus at a point on the ground surface of the Earth has been known to be 47° due to astronomical observation. Provided that the shortest distance between the Earth and the Venus at conjunction is measured directly with laser-light application, a simple trigonometry calculation gives us the distance of the Earth and the Sun. The result becomes of course the same as the one obtained from the other calculation mentioned above.

With the knowledge of the distance between the Earth and the Sun, we are now to estimate the diameter of the Sun. According to the angle subtended by the diameter of a solar disc that can be seen from the ground surface is 0.532°, which is almost equivalent to the angle subtended by the diameter of the hole of a fifty-yen coin held by your thumb and index finger at a stretch of your right or left arm. Since we now know the distance between the Earth and the Sun as 1.5×10^{11} m, the diameter of the Sun can be easily estimated by multiplying the distance value, 1.5×10^{11} m, and the angle value in radian, 0.00928. The result is 1.39×10^{9} m.



$$\frac{D}{1.5\times10^{11}} = \frac{5}{540}$$

Acknowledgments The discussion in 2.5 is based on the piece of work primarily made by I. Takahashi.

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Springer

http://www.springer.com/978-1-4471-4572-1

Exergy
Theory and Applications in the Built Environment
Shukuya, M.
2013, XII, 368 p., Hardcover
ISBN: 978-1-4471-4572-1