# Part IV

# VARIOUS FACTORS AFFECTING THE EVOLUTION OF THE EARTH'S CLIMATE

# 13

# Earth's Orbital Distance from the Sun

## Effect of Gravity on Earth's Orbital Paths

Every object in the universe is attracted to every other object in the universe by a force called gravity. Neutron identified mass and separation-distance as the important constituents of the universal force of gravity, *F.* Gravity, g, is one of the weakest forces in the universe. Between any two objects, the force, *F*, is dependent on the quantity of mass of each object and the inverse of the square of the distance between their centers of gravity.

$$F = \frac{g m_1 m_2}{d^2} \tag{13.1}$$

where: $g$ is the gravitational constant, $g = 6.674 \times 10^{-11}$ N (m²/kg²); $m_1$ (kg) is the mass of the first object; $m_2$ (kg) is the mass of the second object and $d$, is the distance (m) between the centers of mass of the two objects.

The gravitational force, *F*, between two objects can be very strong, even if only one of the objects is massive. If the objects are separated by a distance, *d*, the force quickly weakens as the distance, *d*, between the centers of gravity increases. It should also be noted in Eq 13.1, that *d*, because it is squared, reduces the force, *F*, between the two objects. An excellent example of this is the comparison of forces, is the difference of the influence between the Sun and the moon on the tides of the Earth's ocean. The Sun is the most massive object in our solar system, with a distance from the Earth of $d_{S-E} \approx 1.50 \times 10^8$ km. It is 333,000 times more massive than the Earth, exerting less force ($F_{S-E}$) on the Earth's ocean tides than the moon ($F_{M-E}$) at a distance $d_{M-E} \approx 3.825 \times 10^5$ km. Yet the mass of the moon is 1/6 the mass of the Earth. Another example of how distance is the most crucial factor in determining the gravitational force is that of a human standing on the Earth ($F_{E-h}$). Inasmuch as the distance between the Sun and a person on the surface of the Earth ($d_{S-h}$), is much greater than the distance between the Earth's center of gravity and the human ($d_{E-h}$) the Sun's gravitational force on the human ($F_{S-h}$) is far smaller than that which the Earth exerts on that person ($F_{E-h}$)

The moon's force on a human is 0.06% of the Sun's force. The same reasoning demonstrates that the force a person feels from the moon is even smaller, or 0.00035% of the Earth's gravitational force. The force from the planet Jupiter, when it is closest to the Earth, is even lower, only 0.0000037% of the Earth's gravitational force (Univ. Calif. Santa Barb., 2016).

The gravitational force between the Sun and the Earth ($F_{S-E}$) is about $3.54 \times 10^{22}$ N. This force is sufficient to keep the Earth orbiting around the Sun. Although this is the primary force that dictates the Earth's orbit about the Sun, gravitational forces from other planets, within our solar system, also affect the Earth's orbit about the Sun to a much smaller degree. The gravitational force of the moon on the Earth is ≈0.55% of the gravitational force between the Sun and the Earth. When Jupiter and Mars are closest to the Earth, Jupiter exerts 0.0062% of this force on the Earth's orbit and Mars only 0.00023% (UCSB, 2016). Other large bodies within the solar system directly affect the Earth's orbit about the Sun, to a much lesser degree, altering the distance ($d_{S-E}$) and thus the quantity of energy the Earth obtains from the Sun.

## Earth's Orbital Path About the Sun

Newton recognized that the reason that one object orbits about another is related to the same gravitational force, *F*, that controls why objects fall to the Earth's surface when they are dropped. As the most massive object in the solar system, the Sun's gravity strongly pulls on every object within the solar system (Figure 13.1). All bodies within the solar system also exert

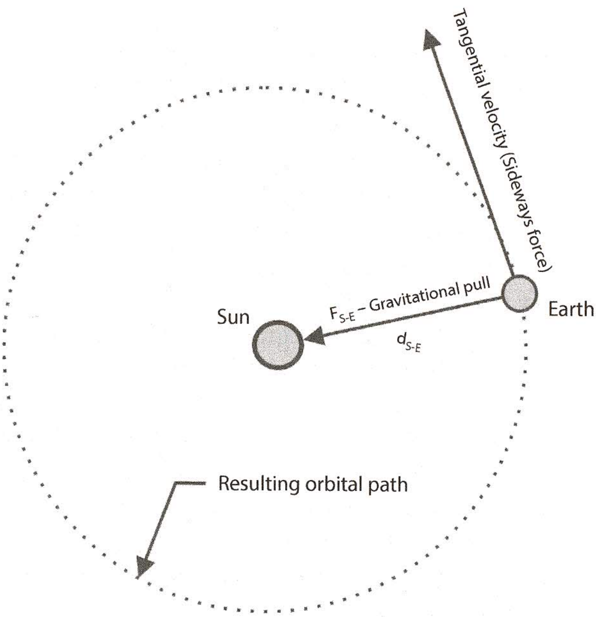



**Figure 13.1** Schematic showing the forces controlling the orbit of the Earth about the Sun due to gravity.

a force (attraction) on each other; however, the force of the pull on the Earth's orbit, is significantly lower than that of the Sun's, as they have much less mass and, in many cases, often a greater distance, *d*, between their centers of gravity (between them and the Earth). Thus, because the Sun has a significantly greater mass than the other planets, all bodies (either directly or indirectly) orbit the Sun (solar system). When smaller solar objects are close enough to larger bodies, e.g., moons close to planets, the bodies with a larger mass are often capable of capturing these objects, forcing them to orbit about the larger body, while both bodies orbit the Sun. The Sun exerts the strongest gravitational pull of any object in our solar system and dominates the solar orbital system. Newton's law can be used to describe the total gravitational force:

$$F = ma, \qquad \text{(Eq. 13.2)}$$

where $m$ represents the objects mass and $a$ is the gravitational acceleration. The force, F in Eq. 13.1 may be used to compute the force between two objects; however, it should be realized that other objects may also have a significant influence on the total force excerted on the object. The total force and its direction is a summation of all the forces on the object.

After examining Figure 13.1, the following question might be asked: "*If the Sun is pulling the planet toward itself, why doesn't the planet just collide with the Sun*?" The answer is: "*in addition to falling toward the Sun, the planet also has a tangential velocity or movement sideways to the Sun within the elliptical plane, generating a force perpendicular to the force of the Sun's gravity*". When the force generated by this sideways velocity of the object and the *force pulling away* equals the gravity (*falling toward*) force, the object orbits the Sun (Figure 13.1). If the tangential velocity is greater, the force pulling away from the Sun is greater than the Sun's gravity force, then the object escapes the pull of the Sun's gravity and leaves the solar system. If the tangential velocity is less, the force pulling away is weaker than the Sun's pull of gravity, the object will crash into the Sun. This is the same force, *F*, one encounters when a weight is fastened to a string and is swung about oneself. As the weight swings around, the string exerts a pull away from one's hand, just as a planet attempts to pull away from the Sun; however, the force of gravity, represented by the pull on the string, prevents the weight escaping. Increasing the tangential velocity of the weight, increases the pull on the string, requiring more force to keep the weight in orbit. Without the tangential velocity, the planet would fall toward the Sun. Likewise, without the pull toward the Sun, the planet would go flying off in a straight line, escaping its orbit. This is what would happen if you let go of the string. For a planet to be held in orbit about the Sun, the force, $F_{away}$, of the object must be equal to the gravitational force, $F_{toward}$, pulling it toward the Sun. The $F_{away}$ is dependent upon the tangential velocity of the planet. At higher velocities, the planet will move a greater distance, *d*, away from the Sun and at lower velocities, it will move closer to the Sun. Figure 13.1 is a schematic illustrating the forces holding a planet in orbit about the Sun. If the tangential velocity is either too high or too low, the planet can either escape or crash into the Sun. The tangential velocity to the Sun of a planet determines the orbital distance, *d*, of the planet from the Sun. The faster the velocity, the further the planet is from the Sun. In effect, a planet orbiting the Sun is continually falling toward the Sun. Planets that are further from the Sun must have greater tangential velocities to remain in orbit.

## Kepler's Laws Pertaining to Planetary Orbits

For a two-body interaction (e.g., Sun and a planet) Kepler's three laws of planetary motion state that: (1) *Law of Orbits*: All planets move about the Sun in elliptical orbits with the Sun at one of the elliptical focus of the orbital path (Figure 13.2). (2) *Law of Areas*: A line that connects a planet to the Sun sweeps out equal areas for equal lengths of time (Figure 13.3); and

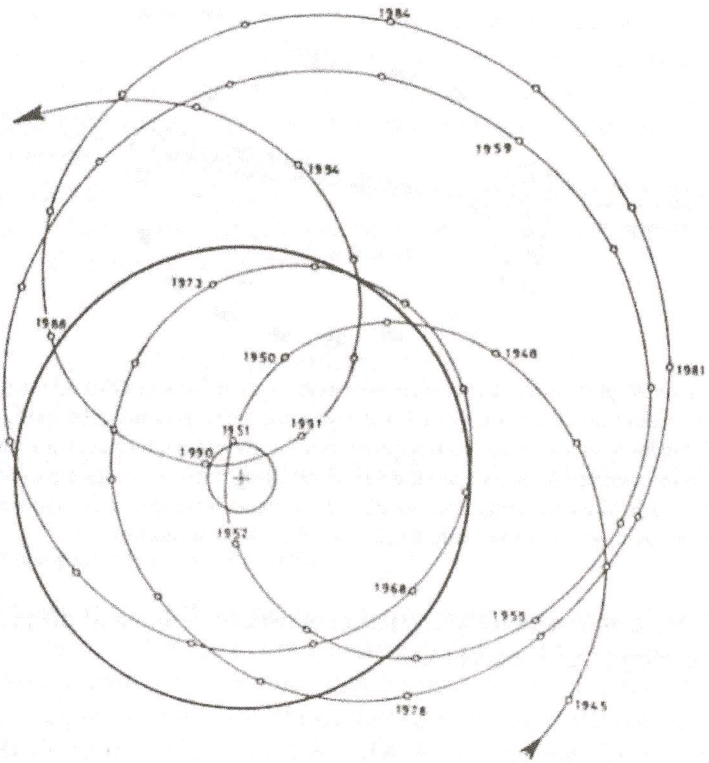



**Figure 13.2** Sun's motion around the solar system's center of mass where the Sun's limb is shown as a thick solid circle. The motion of the Sun's center of mass between 1945 and 1995 is shown by the thinner curves with the years listed. (After Landscheidt, 2003.)

(3) *Law of Periods*: The square of the period for any planet is proportional to the cube of the semi-major axis of its orbit (Figure 13.4) (Daugherty, 2006).

At all times, as the planets travel along their orbit about the Sun, energy is exchanged and conserved. The momentum of the planet is always conserved as described by Newton's *Law of Conservation of Energy*:

$$\textit{Potential Energy} + \textit{Kinetic Energy} = \textit{Constant} \quad \text{(Eq. 13.3)}$$

The potential energy, *PE* is:

$$PE = mad\,, \quad \text{(Eq. 13.4)}$$

where $m$ represents the mass of the planet and $d$ the distance between the Sun and the planet. $a$ is the acceleration of the mass of the planet caused

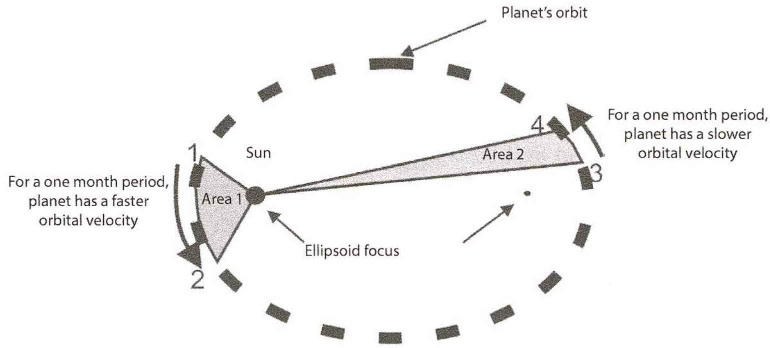



**Figure 13.3** Kepler's three laws of planetary motion are reflected in this schematic of the orbit of a planet about the Sun. *Area 1* is always equal to the area swept by *Area 2*. The planet's position on the orbital path requires that the gravitation forces are greater on the planet at the shorter distances from the Sun, *d*, resulting in greater tangential velocities along the path. Thus, the tangential velocity of the planet increases or decreases in velocity as it moves through its orbital path. At all times PE + KE = a constant.

by the force of gravitational attraction between the Sun and the planet. The kinetic energy, *KE* is equal to:

$$KE = \frac{1}{2}v^2, \qquad \text{(Eq. 13.5)}$$

where $v$ is the velocity of the planet about the Sun. Newton's law of the conservation of energy describes why the planet varies its velocity as it follows its orbit about the Sun. Figure 13.2 is a schematic illustrating the mechanics of a planet orbiting about the Sun. Kepler recognized that all planetary orbits within our solar system are ellipses, with the Sun located at one focus (Figure 13.2). The distance, $d$, between the centers of gravity of the two bodies varies as the planet moves about its orbit (13.5). When the planet is the furthest, $d_{max}$, from the Sun, it is at its aphelion (apogee), the *PE* is at its greatest value (the distance, $d$, is at its greatest value) and the *KE* is the lowest value (tangential velocity is at its lowest). When the planet is closest to the Sun, $d_{min,}$ it is at its perihelion (perigee) of its elliptical orbit, the *PE* is at its lowest value (the distance, $d$, from the Sun is at its shortest) and the *KE* is at its greatest value (the tangential velocity is at its maximum value). Because $d$ is the shortest distance from the Sun at its the planet at its perigee, the quantity of energy transferred from the Sun to the planet is also the greatest, resulting in a higher global temperature for that portion of its orbit. The planet's axis angle of tilt determines the quantity (concentration) of energy transferred to the planet (see discussion in Chapter 3).

Two factors control the quantity of energy transferred between the two bodies for a distance, *d*: (1) the quantity of energy transmitted at that distance and (2) the difference in the tilt between the two bodies or the angle of precession controls the concentration of energy transmitted (for a more detailed discussion, see Chapter 3).

Figure 13.6 describes the quantity of energy that is transmitted over a distance, *d*. Mathematically this quantity of energy, *e*, transmitted over a distance, *d*, decreases by a factor of:

$$\text{Energy transmitted, } e = e_o\left(\frac{1}{d^2}\right), \qquad \text{(Eq. 13.6)}$$

where $e_o$ is the initial quantity of energy being transmitted at $d = 0$.

## Eccentricity of an Object's Orbit

The measure of the difference in shape between a circle and ellipse is referred to as eccentricity, ε. The eccentricity for a circle is zero and the value ε varies from 0 to 1 as the orbit becomes more elliptical, tending toward a straight line for ε = 1. The orbital eccentricity of the solar system's planets is listed in Table 13.1. This table shows that planets, other than Pluto which has a large eccentricity (ε = 0.248), have almost circular orbits. However, since Pluto is no longer considered as a planet, Mercury now has that honor, with ε = 0.2056. The eccentricity of an orbit may be calculated by the following equation:

$$\varepsilon = \left(\frac{d_{max} - d_{min}}{d_{max} + d_{min}}\right), \qquad \text{(Eq. 13.7)}$$

where ε is defined as the coefficient of variation of the maximum and minimum orbital axis.

As indicated in Figure 13.3, a line that connects a planet in its orbit to the Sun, for an equal period of time, sweeps out equal areas. In this example, movement from point 1 to 2 (area A) is a much longer orbital distance than that from point 3 to 4 (area B). In this case, the same time is required for the planet to sweep both areas A and B. The distance of the orbital path from point 1 to 2 is shorter than from point 3 to 4, but because the tangential velocities between the two points differ, the time elapsed for sweeping both areas is the same.

**Table 13.1** Planetary orbit dimensions. (Data from Unv. Calif. Santa Barb., 2016.)

| Planet | Orbital, semimajor axis (astronomical Units) | Orbital period, years | Orbital eccentricity, e |
|---|---|---|---|
| Mercury | 0.387 | 0.241 | 0.206 |
| Venus | 0.723 | 0.615 | 0.007 |
| Earth | 1.000 | 1.000 | 0.017 |
| Mars | 1.524 | 1.881 | 0.093 |
| Jupiter | 5.203 | 11.86 | 0.048 |
| Saturn | 9.539 | 29.46 | 0.056 |
| Uranus | 19.19 | 84.01 | 0.046 |
| Neptune | 30.05 | 164.8 | 0.010 |
| Pluto | 39.53 | 248.6 | 0.248 |

Kepler also recognized the *Law of Periods*, noting that the square of a planet's period, $T$, is proportional to the cube of the semi-major axis, $a$, of the planets orbit (Figure 13.4):

$$T^2 = \frac{4\pi^2}{GM}a^3, \qquad \text{(Eq. 13.8)}$$

where $T$ = time (yr); $a$ = astronomical units (AU); and $M$ = solar mass.

Table 13.2 is the NASA's planetary fact sheet for our solar system. It should be noted that the mass of the Sun at $1.989 \times 10^{30}$ kg is so dominant in the solar system, that: (1) all bodies in the solar system revolve about the Sun; (2) the planetary orbits are almost circular, ($\varepsilon \approx 0$) and, (3) although the other planets exert a gravitational force on each other, the effect they have on each other's orbital path is significantly small.

The following equation can be utilized for calculation of orbits of moons about planets where the mass of one body does not overwhelm the mass of the orbiting body:

$$T^2 = \frac{4\pi^2}{G(M_1 + M_2)}a^3 \qquad \text{(Eq. 13.9)}$$

## Effect of Other Planets on Earth's Orbit

The Sun is positioned at one elliptical focus where the solar system orbits about it. Unlike the Sun with most of the solar system's mass, the other

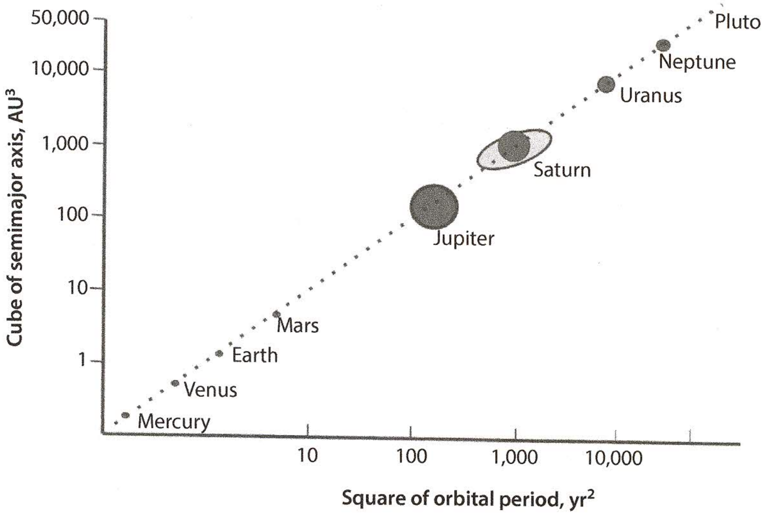



**Figure 13.4** Schematic illustrating Kepler's Law of Periods. The straight dotted line expresses Kepler's Law of Periods. (Data from Daugherty, 2006.)

planets have only a minor gravitational effect on Earth's orbital path due to their small mass (see Table 13.2). The Sun contains about 99% of the mass of the solar system and forces all bodies within the solar system to orbit about it. However, other planets do exert a gravitational force on: (1) the orbital path of the other planets and (2) those bodies (moons) which orbit the planet while also revolving about the Sun. All bodies within the solar system exert a gravitational force on each other's orbital path within the solar system.

Table 13.2 lists several massive planets that have sufficient mass to affect the Earth's orbital path. Jupiter is the second most massive object within the solar system and far more massive than the other planets. The effect of Jupiter's gravitational pull on the Earth's orbital path varies with the distance ($d_{E\text{–}J}$) between the centers of gravity of the two planets. The overall gravitational force of Jupiter on Earth's orbit is much smaller than that of the Sun due to: (1) the greater distance ($d_{E\text{–}J}$) of the Earth to Jupiter and (2) the lesser mass of Jupiter compared to that of the Sun. Likewise, even the smaller massive planets, e.g., Saturn, Neptune, etc., affect the Earth's orbital path, but to a far lesser degree as they are at a greater distance and have significantly less mass. Thus, all the material in the solar system to some degree influence the final shape of the Earth's orbit. The distance ($d$) between the Earth and Sun directly affects the quantity, or concentration, of the energy transmitted (see Figure 13.6), reaching the Earth's surface and determining the Earth's temperatures.

**Table 13.2** Planetary fact sheet in United States units. (Data obtained from NASA, 2018; https://w.w.w.nssdc.gsfc.nasa.gov/planetary/-planetfact.html.)

| | **Mercury** | **Venus** | **Earth** | **Moon** | **Mars** | **Jupiter** | **Saturn** | **Uranus** | **Neptune** | **Pluto** |
|---|---|---|---|---|---|---|---|---|---|---|
| Mass (1021 tons) | 0.364 | 5.37 | 6.58 | 0.81 | 0.708 | 2093 | 627 | 0.5.7 | 113 | 0.0161 |
| Diameter (miles) | 3032 | 7521 | 7926 | 2159 | 4221 | 88,846 | 74,897 | 31,763 | 30,725 | 1464 |
| Density (lbs3.39/$ft^3$) | 339 | 327 | 344 | 209 | 246 | 83 | 43 | 79 | 102 | 131 |
| Gravity ($ft/s^2$) | 12.1 | 29.1 | 32.1 | 5.1 | 12.1 | 75.9 | 29.4 | 28.5 | 36.0 | 2.3 |
| Escape Velocity. (miles/s) | 2.7 | 6.4 | 7.0 | 1.5 | 3.1 | 37.0 | 22.1 | 13.2 | 14.6 | 0.8 |
| Rotation Period (hrs) | 1407.6 | −5832.5 | 23.9 | 655.7 | 24.6 | 9.9 | 10.7 | −17.2 | 16.1 | −153.3 |
| Length of day (hrs) | 4222.6 | 2802.0 | 24.0 | 708.7 | 24.7 | 9.9 | 10.7 | 17.2 | 16.1 | 153.3 |
| Distance from Sun ($10^6$ miles) | 36.0 | 67.2 | 93.0 | 0.239* | 141.6 | 3670.0 | 890.8 | 1784.8 | 2793.1 | 3670.0 |
| Perihelion ($10^6$ km) | 28.6 | 66.8 | 91.4 | 0.226* | 128.4 | 460.1 | 840.4 | 1703.4 | 2761.6 | 2756.9 |
| Aphelion ($10^6$ km) | 43.4 | 67.7 | 94.5 | 0.252* | 154.9 | 507.4 | 941.1 | 1866.4 | 2824.5 | 4583.2 |
| Orbital Period (days) | 88.0 | 224.7 | 365.2 | 27.3 | 687.0 | 4331 | 10,747 | 30,589 | 59,800 | 90,560 |
| Orbital Velocity (miles/s) | 29.4 | 21.8 | 18.5 | 0.64 | 15.0 | 8.1 | 6.0 | 4.2 | 3.4 | 2.9 |
| Orbital inclination (deg.) | 7.0 | 3.4 | 0.0 | 5.1 | 1.9 | 1.3 | 2.5 | 0.8 | 1.8 | 17.2 |
| Orbital Eccentricity | 0.205 | 0.007 | 0.017 | 0.055 | 0.094 | 0.049 | 0.057 | 0.046 | 0.011 | 0.244 |
| Obliquity to Orbit (deg.) | 0.034 | 177.4 | 23.4 | 6.7 | 25.2 | 3.1 | 26.7 | 97.8 | 28.3 | 122.5 |
| Temperature, mean (°F) | 333 | 867 | 59 | −4 | −85 | −166 | −220 | −320 | −330 | −375 |
| Surface pressure (atm.) | 0 | 91 | 1 | 0 | 0.01 | unknown | unknown | unknown | unknown | 0.0001 |
| Number of Moons | 0 | 0 | 1 | 0 | 2 | 67 | 62 | 27 | 14 | 5 |
| Ring System | No | No | No | No | No | Yes | Yes | Yes | Yes | No |
| Global Magnetic Fields | Yes | No | Yes | No | No | Yes | Yes | Yes | Yes | Unknown |

*Relative to Earth, not Sun

The patterns of interaction between the solar system's Sun and its revolving bodies, due to gravitational forces, started as early as the initial accretion stage from the protoplanetary cloud. The Sun ejects a high-energy stream of charged particles, often referred to as the solar wind, that sweeps all gas and volatile components from the Sun into the distant periphery of the solar system. This is a continuous flow of charged particles streaming from the Sun in all directions at speeds of ≈400 km/s or ≈1 million miles per hour. The source of the solar wind is the Sun's hot temperature of the corona. The temperature of the corona is so high that the particles within the corona have velocities that are at and/or above the escape velocity from the Sun's gravity. The solar wind is not uniform, although it is always directed away from the Sun. It changes speed and carries with it (1) magnetic clouds, (2) interacting (turbulent) regions where higher speed wind catches up and mixes with slower speed winds, and (3) has compositional variations. The chemical differentiation of the protoplanetary cloud's matter was affected by the heating of the Sun on the disk's main area, at the earlier stage of its compression and especially after nuclear reactions were initiated within it (Sorokhtin, 2006).

Because of the mechanisms of interaction, condensation occurred in the central areas of the protoplanetary disk, mostly refractory elements and compounds with high ionization potential of refractory metals, e.g., Fe, Ni and oxides of $A1_2O_3$, CaO, MgO, $Ti_2O_3$, $SiO_2$, $Cr_2O_3$, FeO. At the same time, there were concentrations of easily fusible and ionized elements (e.g., Li, Na, K, Rb). Ba and rare earth elements (e.g., Hg, & Pb) within this part of the protoplanetary cloud were very low. To a lesser degree, the elements forming the Earth were impoverished in sulphur, zinc, tin and some other elements. The gas components, e.g., $H_2$, He and other noble gases, $H_2O$, CO, $CO_2$, $CH_4$, $NH_3$, $H_2S$, $SO_2$ and $SO_3$, HC1, HF were almost completely swept out of the internal areas of the protoplanetary cloud and concentrated at its periphery, where they subsequently formed the giant-gas-planets possessing massive and high-density gas shells, e.g., Jupiter (see Table 13.2) (Sorokhtin *et al.*, 2013).

Jupiter is the second most massive object in the solar system, and it has the second strongest effect, although weaker, on the shape of Earth's orbital path. The overall gravitational force of Jupiter on Earth's orbital path is much smaller than that of the sun due to Jupiter's far greater distance and lesser mass than the Sun. Likewise, the smaller, less massive planets, e.g., Saturn, Neptune, etc., affect Earth's orbit to a slighter degree than Jupiter. At any time along Earth's orbit, the distance of the Sun to the Earth directly affects the quantity of energy reaching the Earth's surface (see Figure 13.6).

Although the gravitational influence of Jupiter and Saturn, along with the lesser bodies of the solar system, affect the Earth's final orbital path

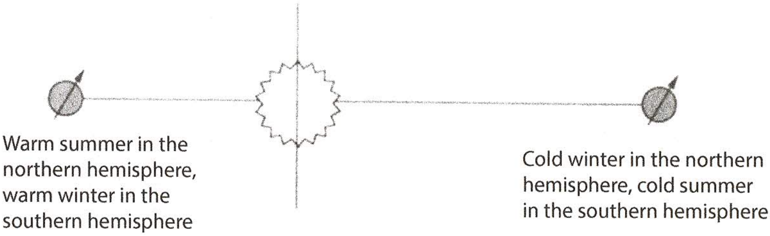



**Figure 13.5** The Earth's yearly hemispheric contrast in distance from the Sun, d, between the summer and winter. The Sun is located in one of the ellipses foci, in Earth's elliptical orbit of revolution about the Sun. The arrows point to the North star and indicate the angle of the Earth's rotation on its axis. The vertical line shows the center of the Sun's mass.

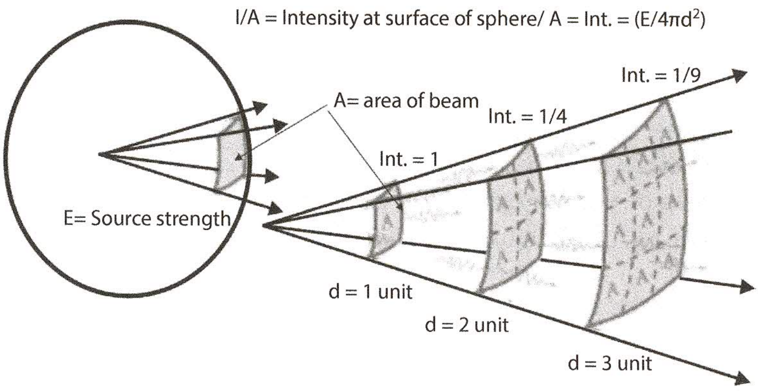



**Figure 13.6** Schematic showing spread of energy, intensity/area of ray, with distance from the source.

about the Sun, they also affect the position of the Sun and other bodies within the solar system (Figure 13.2). The result is a complex picture of Earth revolving around the Sun in an elliptic orbit, with average orbital ellipticity of ≈0.017 (Table 13.2). Thus, the Earth during a single revolution (i.e., in one year), varies with the distance, *d*, from the Sun (which is in one of the foci of Earth's elliptical orbit); the change in the other planet positions with time directly affects Earth's orbital path (Figure 13.5). No two sequential years have the same orbital path, resulting in a cyclical variation of temperature with respect to time.

Today, the ellipticity for the Earth's orbit and average distance of the Earth to Sun is ≈149 million km. The pericenter of Earth's orbit is ≈1.48 million km (92 million miles) and the apocenter, ≈1.53 million km (95.1 million miles) (see Figure 13.7). Therefore, Earth to the Sun distance,

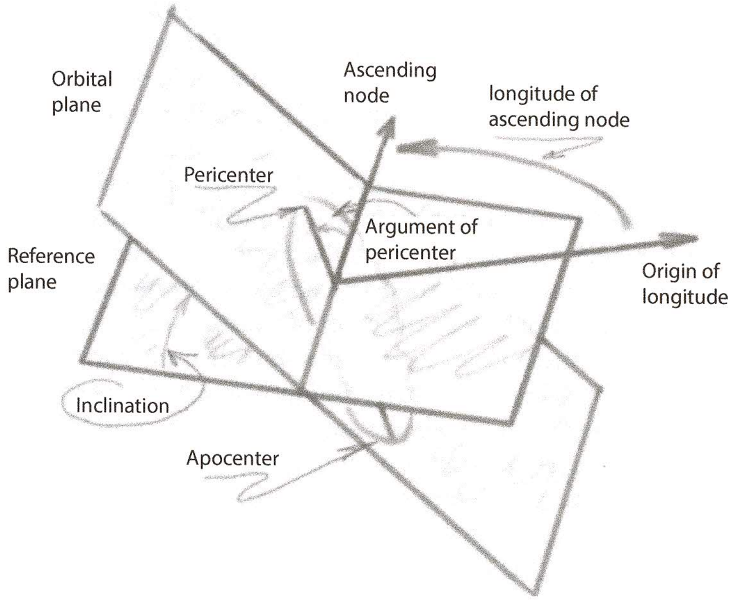



**Figure 13.7** Parameters describing elliptical orbits: (1) Apocenter – The location of the greatest distance between the orbiting body and the central body when the orbit is an ellipse. The apocenter is diametrically opposite the pericenter on the major axis of the orbit. (2) Pericenter—The shortest distance between the center of the orbiting body and the center of the orbited body. (After Cornell, 2017. https://www.classe.cornell.edu/~seb/celestia/orbital-parameters.html.)

*d*, varies by ≈5 million km (3.1 million miles). The solar insolation of Earth is always in inverse proportion with the squared distance between the Sun and Earth. This results in the annual variation of Earth's temperature, which is affected by the Sun's constant between 1.41 to $1.32 \times 10^6$ erg/cm$^2$ or an average $S_0 = 1.367 \times 10^6$ erg/cm$^2 \cdot$ s. According to Monin and Sonechkin (2005), the Sun to Earth distance, *d*, varies between 1.47- to 1.52-million km (91.4 and 94.5 million miles) with the Sun constant, between 1.428- to $1.322 \times 10^6$ erg/cm$^2$. The following equation:

$$T = b^{\alpha}\left[\frac{S(1-A)}{\sigma\left(4\left(\frac{\left(\frac{\pi}{2}-\psi\right)}{\frac{\pi}{2}}\right)+4\left(\frac{\psi}{\frac{\pi}{2}}\right)\left(\frac{(1-\cos\psi)}{(\sin\psi)^2}\right)\right)}\right]^{\frac{1}{4}}\left(\frac{p}{p_o}\right)^{\alpha} \quad \text{(Eq. 2.25)}$$

shows that variations of the solar constant may correspond to the average values of the near-surface temperature of 288.5 K and 290.2 K, with fluctuations of up to 4.7 °C. These fluctuations, however, have a seasonal nature and apparently have negligible effect on the Earth's average temperature.

As a result, when the Earth is coming through the perihelion, its average temperature annually increases by 2.2 °C and in aphelion, on the contrary, declines by 2.5 °C. Depending on the Earth's revolution axis orientation relative to the direction to the Sun, climatic contrasts in different seasons appear (see Figure 13.5). At the onset of a cooler winter and warmer summer in the Northern Hemisphere and simultaneously a warmer winter and a cooler summer in the Southern Hemisphere. Examples of such contrasting seasons are the severe winters and hot summers of 1940-1941 or on the contrary, warm winters and cool summers of 1983-1984. It should be kept in mind that the real picture of climatic variations is much more complex due to superposition of the Sun's motion around the solar system mass center and the Earth's revolution around the Sun.

## The Effect of the Planet Jupiter on Earth's Orbital Path

Jupiter is the largest planet in the Solar system and its mass, $m_J \approx 1.90 \times 10^{24}$ kg is ≈318 times greater than that of the Earth, $m_E \approx 5.97 \times 10^{24}$ kg. Minimum distance between the Earth and Jupiter ($d_{J\text{-}E\text{-}min}$) (at the planet's opposition point on the apsis) is approximately $6.3045 \times 10^{13}$ cm, where the maximum distance ($d_{J\text{-}E\text{-}max}$) (also on the apsis) is $\approx 9.3045 \times 10^{13}$ cm. Therefore, the maximum gravitational pull from Jupiter on the Earth is equal to:

$$F_{J-E_{max}} = \gamma \left[ \frac{m_J \times m_E}{d_{J-E_{min}}} \right] = 1.936 \times 10^{23} \text{ dynes}, \qquad \text{(Eq. 13.10)}$$

and the minimum is:

$$F_{J-E_{min}} = \gamma \left[ \frac{m_J \times m_E}{(d_{J-E_{max}})^2} \right] = 8.758 \times 10^{22} \text{ dynes}. \qquad \text{(Eq. 13.11)}$$

where $\gamma = 6.67 \times 10^{-8}$ cm$^3$/g-s$^2$ is the gravitational acceleration.

The gravitational pull on the Earth by the Sun is greater by an order of magnitude than that of the Earth by Jupiter. The mass of the Sun,

$m_S \approx 1.99 \times 10^{33}$ g, and the distance between the Sun and the Earth is much smaller: $d_{S-E} \approx 1.496 \times 10^{13}$ cm. In this case the average gravity pull by the Sun on the Earth is equal to:

$$F_{S-E} = \gamma \left[ \frac{m_E \times m_S}{(d_{SE})^2} \right] = 3.5166 \times 10^{27} \text{ dynes}. \quad \text{(Eq. 13.12)}$$

The difference between the gravity forces by the Sun and Jupiter on the Earth's orbital path at the moment of their crossing the apsis is to:

$$\Delta F_{\min} = 3.5166 \times 10^{27} - 1.936 \times 10^{23} = 3.5164 \times 10^{27} \text{ dynes}, \quad \text{(Eq. 13.13)}$$

$$\Delta F_{\max} = 3.5166 \times 10^{27} - 8.758 \times 10^{23} = 3.5165 \times 10^{27} \text{ dynes}. \quad \text{(Eq. 13.14)}$$

Thus, the difference between the maximum and minimum forces acting between the Jupiter and the Earth at their opposition and that of Jupiter in the contrary position is:

$$\Delta F = 3.5165 \times 10^{27} - 3.5164 \times 10^{27} \approx 1 \times 10^{23} \text{ dynes}. \quad \text{(Eq. 13.15)}$$

Other planets within the solar system, e.g., Saturn and Mars, render a much smaller effect on Earth's orbital path. The interaction forces between Saturn and Earth at the point of planetary opposition is $F_{Sat\text{-}E} = 1.395 \times 10^{22}$ and for Mars and Earth is $F_{Mar\text{-}E} = 4.605 \times 10^{21}$ dynes.

Earth's revolution around the Sun occurs around the center of mass between the Sun and Jupiter. This center, with the average Jupiter-Sun distance of $d_{S\text{-}J} \approx 7.8 \times 10^{13}$ cm, is offset from the Sun's center of mass by:

$$x = d_{S-J} \left[ \frac{M_J}{M_S} \right] = 7.454 \times 10^{10} \text{ cm}. \quad \text{(Eq. 13.16)}$$

This distance is outside of the Sun's body, as the radius of the Sun's is $r_S = 6.96 \times 10^{10}$ cm.

The time required for one revolution of Jupiter around the Sun is 11.862 years. The period of interaction between the Earth and Jupiter, and of Jupiter's effect on the position of Earth's orbit at any time would also be about 11.862 years. One might anticipate that under the pull of gravity from the external planets, the Earth's orbit would be changing its direction of ellipticity over the same period. Earth's revolution around the Sun represents a huge *gyroscope* and thus is quite stable (see Table 13.3). The apsis running through the center of the Sun and connecting the points of perihelion (closest approach of Earth to the Sun) and aphelion (largest distance between the Earth and the Sun) is quite stable. This precession of the Earth equals 93,000 years and over the foreseeable future, one would not anticipate the position of the apsis to change appreciably. The effect of this cycle on Earth's temperature is reflected in its 100,000-year cycles as reflected on the long-term temperature charts (see Figure 10.17).

The minimum and maximum distances between the Sun and the Earth can be calculated by Eq. 13.16:

$$d_{S-E_{min}} = 1.5\times10^{13} - 7.457\times10^{10} = 1.4925\times10^{13}\,\text{cm},$$

and

$$d_{S-E_{max}} = 1.5\times10^{13} + 7.457\times10^{10} = 1.5075\times10^{13}\,\text{cm}.$$

The average value of the solar constant $S = 1.367 \times 10^6$ erg/ cm$^2 \cdot$ s. Thus, the maximum and minimum values of the solar constant are:

$$S_{max} = 1.367\times10^6\left[\frac{1.5\times10^{13}}{1.4925\times10^{25}}\right]^2 = 1.381\times10^6\,\text{erg/cm}^2\cdot\text{s},$$

and

$$S_{min} = 1.367\times10^6\left[\frac{1.5\times10^{13}}{1.5075\times10^{25}}\right]^2 = 1.353\times10^6\,\text{erg/cm}^2\cdot\text{s}.$$

At the Earth's precession angle, $\omega = 23.44°$, albedo $A = 0.3$, normal atmosphere of pressure, $p = 1$ atm., and temperature in degrees Kelvin is:

$$T = 1.093\left[\frac{S(1-A)}{3.5\sigma}\right]^{\frac{1}{4}}, \qquad \text{(Eq. 13.17)}$$

where $\sigma = 5.67 \times 10^{-5}$ erg/cm$^2 \cdot$ s $\cdot$ deg$^4$ (the Stefan-Boltzmann constant). Thus:

$$T_{\max} = 1.093\left[\frac{(1.381\times10^{6})0.7}{\left(5.67\times10^{-5}\right)3.5}\right]^{\frac{1}{4}} = 288.756\ \text{K},$$

and

$$T_{\min} = 1.093\left[\frac{(1.353\times10^{6})0.7}{(5.67\times10^{-5})3.5}\right]^{\frac{1}{4}} = 287.281\ \text{K}.$$

The difference between these temperatures is $\Delta T \approx 1.475$ °C. This difference in value is caused by the Jupiter gravitational effect. Although small, it could likely increase due to the synoptic activity of the atmosphere and changes in the Earth's albedo, e.g., due to the snow cover in winter with simultaneous increase in the cloud cover. The value of the factor $k$ in the following equation, for this increase is unclear:

$$k = \frac{F_S - F_Y - F_{St} - F_M}{F_S + F_Y + F_{St} + F_M} = 0.999876. \qquad \text{(Eq. 13.18)}$$

In the authors' estimate, it may be much greater than 2 as the annual average temperatures practically do not change.

The elongation of the Earth's elliptical orbital path is in proportion to the difference in the gravity pull from the Sun and the closest external planets (Mars, Jupiter and Saturn). The largest eccentricity of Earth's orbit occurs at the point of its aphelion during the planetary alignment, i.e., when the positions of Mars, Jupiter and Saturn coincide. The maximum eccentricity is determined by the following equation:

$$\varepsilon^2 = (1 - k^2). \qquad \text{(Eq. 13.19)}$$

Thus, $\varepsilon \approx 0.01578$. This eccentricity value is close to the observation data: $\varepsilon = 0.0167$. The small difference, most likely, is due to inaccuracies in the determination of planetary masses and their distances from the Earth. However, the largest effect on the Earth's orbital path is exerted primarily by Jupiter:

$$k_J = \frac{F_S - F_J}{F_S + F_J} 0.999886 \text{ and } \varepsilon_J = 0.01507, \qquad \text{(Eq. 13.20)}$$

which is responsible for 95.5% of the Earth's eccentricity.

The question is, how does Jupiter's gravity affect the Earth's elliptical orbit? When the Earth's apsis corresponds with the direction toward Jupiter, some offset of the focus (in which the Sun is positioned) of the Earth's elliptical orbit occurs toward the center of the Sun-Jupiter mass by the amount determined by the interrelation of forces acting from the side of Jupiter and the Sun:

$$\Delta d_{S-J} = d_{S-J}\left[\frac{m_J}{m_S}\right] = 7.8045\times 10^{13}\left[\frac{1.9007\times 10^{30}}{1.99\times 10^{33}}\right] = 7.4543\times 10^{3}\,\text{cm}\,.$$

(Eq. 13.21)

A similar offset of the focus length occurs both at Jupiter's intersection of apsis from the side of aphelion and of the perihelion. For this reason, the distance between the Earth and the Sun, affected by Jupiter's gravity pull, changes from: $d_{S-E\min} = (1.5\times 10^{13}) - (7.4543\times 10^{10}) = 1.4925\times 10^{13}\,\text{cm}$, (Eq. 13.22) to

$$L_{S+E\max} = (1.5\times 10^{13}) + (7.4543\times 10^{10}) = 1.5075\times 10^{13}\,\text{cm}\,. \quad \text{(Eq. 13.23)}$$

According to the adiabatic theory of the greenhouse effect (Sorokhtin 2006; Sorokhtin *et al.*, 2007, 2011), the average absolute temperature of the planet's troposphere $T$ (in degrees Kelvin) is a function of the Sun constant, $S$, and the atmospheric pressure, $p$, as reflected in Eq. 2.22, where $S = 1.367 \times 10^6$ erg/cm² · s is the solar constant (flow of the solar energy reaching the Earth); $\sigma = 5.67 \times 10^{-5}$ erg/cm² · s · °C⁴ is the Stefan-Boltzmann constant; $A$ is the planet's reflectivity (albedo), for the Earth $A \approx 0.3$; $p_0$ is the unit of pressure, e.g., $p_0 = 1$ atm; the scaling factor, $b = 1.597$; $\alpha$ is the adiabatic exponent, $\alpha = (\gamma - 1/\gamma)$; $\gamma = (c_p/c_v)$ where $c_p$ and $c_v$ are the specific heats of gas at constant pressure and constant volume, respectively; $\psi$ is the angle of precession (Earth's value today is $\psi = 23.44°$). At $\psi = 23.44°$, the denominator in Eq. 3-27 is equal to 3.502 rather than 4.0 in the classic format at $\psi = 0$.

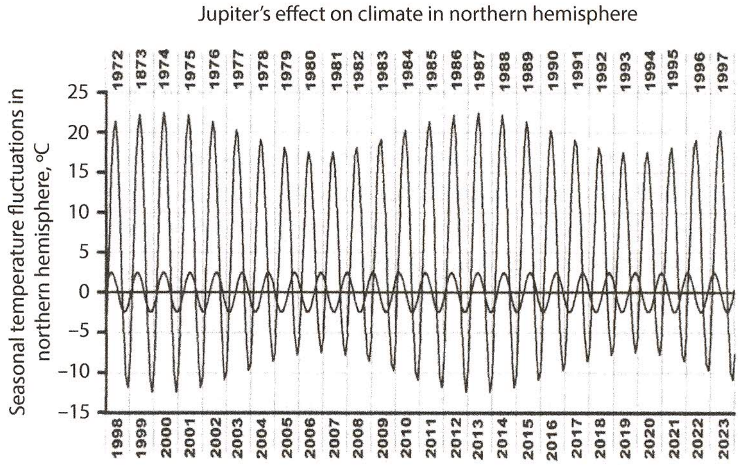
Changes in the solar constant by 0.1 to 0.2 % in Eq. 2-26 result in changes of Earth's near-surface temperature by 0.072 to 0.143 °C. Much larger temperature fluctuations are caused by the Earth's axis precession. Considering the quoted Earth's orbit eccentricity value and the average of the Earth to the Sun distance ($d_{S-E} \approx 150$ MM km), it is possible to determine that the Earth's orbit perihelion is ≈147.4 MM km and its aphelion ≈152.6 MM km. This shows that the change in Earth to the Sun distance may exceed 5 MM km. The solar insolation of Earth is always inversely proportional to the square of the Sun-to-Earth distance, $d_{S\text{-}E}$, causing annual fluctuations in the solar constant by 1.416 to 1.321 × $10^6$ erg/cm$^2$ · s, with an average value of $S_0$ = 1.367 × $10^6$ erg/cm$^2$ · s. These changes in the solar constant value, shown in Eq. 2.26, correspond with the Earth's average near-surface temperature of 285.5 to 290.5 K, or its fluctuations by up to ±2.5 °C. These fluctuations, however, are seasonal and apparently have no significant effect on the Earth's average annual temperature.

Thus, during the Earth's passage of the perihelion, its average temperature approximately increases annually by 2.5 °C; in the aphelion, on the other hand, it decreases by about the same 2.5 °C. Depending on the Earth's revolution axis direction (relative to the direction to the Sun), this results in climatic contrasts during the opposite seasons. For instance, the onset of a cool winter and hot summer in the Northern Hemisphere and simultaneously warm winter and cool summer in the Southern Hemisphere (warm autumn and cool spring or warm spring and cool autumn) at the average climatic parameters of these seasons (see Figure 13.5).

Earth's climatic fluctuations are likely much more complex due to the superposition of the Sun's motion around the solar system's center of mass, the movement of the other planets effecting the Earth's orbital path around the Sun. As shown in Figure 10.17, these fluctuations in Earth's orbital path are affected by: (1) the gravity pull from the other planets, primarily Jupiter and Saturn, and (2) the Sun delineates rather complicated trajectories in its movement around the solar system's center of mass as shown in Figure 13.2. Together with the Sun, the Earth's orbit delineates similar *pirouettes*. The Earth's elliptic orbital focus is always close to the Sun's center of mass, thus the general image of the Earth revolving around the Sun on the elliptic orbits is complex.

The pull of gravity from the planets revolving around the Sun, affect not only the orbit of the Earth and all other planets, but also the position of the Sun itself relative to the solar system's center of mass and their orbital paths (see Figure 13.2).

Temperature fluctuations of ±2.5 °C caused by the Earth's revolution around the Sun on an elliptic orbit, influence the amplitude of the Earth's seasonal temperature changes. One period of cyclical influence by Jupiter on the climate is ≈11.86 Earth years, whereas the Earth's seasonal temperature fluctuations are exactly 12 months. Thus, the superposition of the large planets' gravitational effect (mostly Jupiter's) on Earth's climate should result in a modulation of the seasonal temperature fluctuations with the amplitude of ±2.5 °C and a total cyclical period of ≈12 years. An estimate of such climatic disturbances of seasonal temperatures at the Earth's



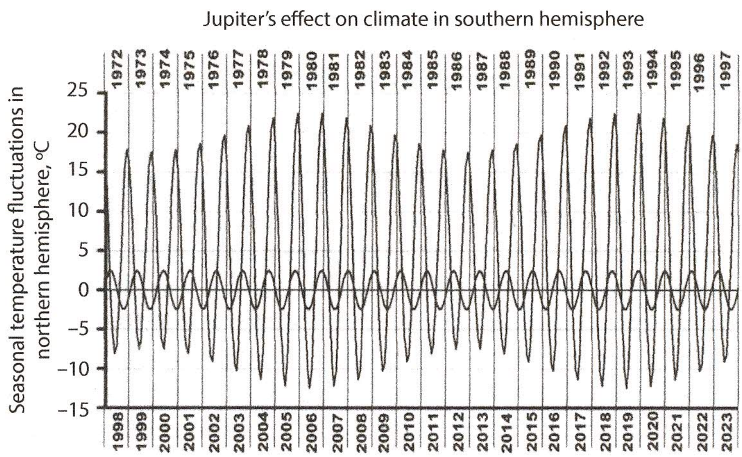




**Figure 13.8** Theoretical effect of Jupiter on the average monthly temperature fluctuations in the Earth's medium latitudes during 1972 through 2023 (for greater time intervals, a more precise consideration of the deviation of Jupiter's revolution period from 12 years is necessary). The Jupiter's effect is determined by its gravity pull on the Earth resulting in the precession of the Earth's elliptic orbit in its revolution around the Sun (the effect of 11-year fluctuation of solar activity does not exceed 0.1 to 0.15oC and may be disregarded here).

mid-latitudes is included in Figure 13.8. The quoted climatic disturbances are usually outside the range of vision of scientists, as the very effect of 13-year modulation by Jupiter's influence disappears due to averaging of seasonal fluctuations in the processing of observations.

Figure 13.8 displays four-time intervals (1978–1983, 1991–1996, 2004–2009 and 2017–2022) in the Northern Hemisphere, which exhibited abnormally warm winters and cool summer seasons. On the other hand, the periods 1972–1978, 1985–1990, 1997–2002 and 2010–2015 had cold winters and warm summers. In the Southern Hemisphere, the situation is inversed. Time intervals of 1978–1983, 1991–1996, 2004–2009 and 2017–2022 had cold winters and warm summer seasons, whereas the periods 1972–1978, 1985–1990, 1997–2002 and 2010–2015 had warm winters and cool summers. This regularity, of course, is quite understandable as cold seasons occur primarily when the Earth goes through the aphelion (i.e., the point of largest distance from the Sun). Exactly in a half a year, when the Earth arrives at the perihelion (i.e., closest to the Sun), the Earth warms up. For instance, in 2006 Earth went through the perihelion on December 3rd and the aphelion on June 6th of 2007. That is why the winter of 2007 in the Northern Hemisphere turned out to be unusually warm and the summer relatively cool, whereas in the Southern Hemisphere the winter was cold and the summer warm.

In 1815, the summer in Europe was cold. The origin of this phenomenon has been attributed to the Tambora volcanic eruption on the Sumbava Island, Indonesia. But contrary to all expectations, the winter was warm and not cold. Again, an analogous situation appears to have occurred in the Northern Hemisphere in 2007: a relatively cool summer (except for rare days when the warm air from the arid belt of the Mediterranean area arrived at the medium latitudes of the Northern Hemisphere) and a very warm winter. If one subtracts 1815 from 2007 we get 192, which is exactly 16 cycles of Jupiter's gravitational action on the Earth's climate ($12 \times 16 = 192$).

In 2006, the temperatures in fall were warmer, December was relatively warm and the snow, as in 1826, fell only in January. The interval between these two events was exactly 180 years (2006-1826). This time interval approximately constitutes 15 cycles of Jupiter's effect on Earth's climate: $12 \times 15 = 180$ years (another option is $11.862 \times 15 = 177.93 \approx 178$ years).

In 1940 and 1941, Europe experienced exceptionally severe winters with bitter frosts in December. Again, a similar climatic situation was observed in 2000 and 2001. The time difference between these events was 60 years or five 12-year cycles of Jupiter's gravitational effect on the Earth's climate. Subtracting from the year 2000, the 60-year period (which is equal to five 12-year cycles) gives the year 1940. Comparable results are obtained for the year 2001: ($2001 - 12 \times 5$ or 1941).

A very warm winter occurred in European Russia in 1947 when at New Year's Eve one could get his feet wet. Again, there is a $12 \times 5$ or 60-year cycle between 2007 and 1947.

This climatic data is approximate and does not consider the effect of continent and ocean positions, ocean currents, and the synoptic activity on the real temperature distribution occurring above the Earth's surface. This may be the reason why comparison of theoretical climatic temperature regime changes with empiric monthly average temperature distributions for the Northern and Southern hemispheres (Figure 13.8) often does not reveal the anticipated data correlation.

The likely reasons for the total mismatch of temperatures may be the result of a strong negative feedback (through the planet's albedo) between the incidental solar radiation and the near-surface temperature. Indeed, any increase in the solar insolation of the Earth's temperature will result in an increased water evaporation from the oceans and, thus, in an increased cloud cover and the Earth's reflectivity (albedo) and decreased solar energy reaching the Earth's surface. As a result, the surface temperature declines to a new equilibrium level. Under a strong negative feedback, such temperature decline may be very substantial, drastically decreasing fluctuations at the set albedo. Thus, the temperature changes due to fluctuations of solar radiation become negligible on the background of stronger synoptic temperature fluctuations, which apparently does occur.

Despite the weakened solar radiation effect on changes in the near-surface temperatures, Jupiter influences the energy processes in the Earth's atmosphere through humidity condensation (the water heat capacity $\approx 1\ \text{cal/g} \cdot \text{deg}$ is significant). It is possible, therefore, that the periodicity in climatic anomalies (droughts, rainy seasons and especially storms) is associated with fluctuations in the solar insolation. This includes those occurring due to the Earth's revolving around the Sun in elliptical orbits, i.e., eventually under the effect of Jupiter's gravity pull on the Earth. The stated climatic changes must also be affected by its complicating long-period fluctuations of the solar insolation associated with the Sun's revolution around the center of mass of the solar system (see Figure 13.2) and by the prolonged changes in the solar activity (most likely, by nuclear synthesis processes within the Sun).

Currently we live near the maximum of a temporary climate warming, which began as early as the seventeenth century when there was no human effect on the climate by the *greenhouse gases* released into the atmosphere. This shows that the current warming is clearly of a natural origin and soon will unavoidably be replaced by a new cooling period. Reflecting on the temperature charts in Chapter one, although the Earth is experiencing temperature cycles, the overall temperature of the Earth has been steadily decreasing over the past 65 MY.

A similar conclusion was also reached by the well-known German climatologist Landscheidt (2003). He published an article: *New Little Ice Age Instead of Global Warming?* In his estimate, regardless of the recent continuing increase of carbon dioxide in the atmosphere by man's activities, there will be only cooling and the onset of a *little ice age* comparable to the one experienced in the seventeenth and eighteenth centuries. The anticipated average temperature decline will be 1 °C or greater.