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The Atmosphere and Ocean

Third Edition

A Physical Introduction

Neil C. Wells

Advancing Weather and Climate Science

Table of Contents

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A PHYSICAL INTRODUCTION
THIRD EDITION

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Series Foreword

Advances in Weather and Climate

Meteorology is a rapidly moving science. New developments in weather forecasting, climate science and observing techniques are happening all the time, as shown by the wealth of papers published in the various meteorological journals. Often these developments take many years to make it into academic textbooks, by which time the science itself has moved on. At the same time, the underpinning principles of atmospheric science are well understood but could be brought up to date in the light of the ever increasing volume of new and exciting observations and the underlying patterns of climate change that may affect so many aspects of weather and the climate system.

In this series, the Royal Meteorological Society, in conjunction with Wiley-Blackwell, is aiming to bring together both the underpinning principles and new developments in the science into a unified set of books suitable for undergraduate and postgraduate study as well as being a useful resource for the professional meteorologist or Earth system scientist. New developments in weather and climate sciences will be described together with a comprehensive survey of the underpinning principles, thoroughly updated for the 21st century. The series will build into a comprehensive teaching resource for the growing number of courses in weather and climate science at undergraduate and postgraduate level.

Series Editors

Peter Inness, University of Reading, UK
William Beasley, University of Oklahoma, USA

Preface to the Third Edition

The third edition of *The Atmosphere and Ocean* is a major revision of the material in previous editions to reflect the very significant changes in the subject. In particular chapters on mathematical modelling and climate change have been added to the new edition. Furthermore, problems and their solutions have been provided for each chapter, which some readers may find useful.

The book is not an exhaustive account of the subject but reflects my interests over the last 40 years in teaching and research of the ocean and atmosphere. I hope it may continue to instil enthusiasm and fascination for a subject which continues to challenge humankind in the 21st century.

I wish to thank the following people: Kate Davis for the drafting and improvement of the figures, Helen Wells for suggesting improvements to the earlier chapters, and Jenny Wells for careful checking of the final manuscript.

Finally I would like to thank the team at John Wiley, both in Chichester, U.K. and Singapore, who have provided a high level of professional support during the development and the production of this edition.

Chapter 1

The Earth within the Solar System

1.1 The Sun and its constancy

Any account of the Earth's atmosphere and ocean cannot be regarded as complete without a discussion of the Sun, the solar system and the place of the Earth within this system. The Sun supplies the energy absorbed by the Earth's atmosphere-ocean system. Some of Sun's energy is converted directly into thermal energy, which drives the atmospheric circulation. A small portion of this energy appears as the kinetic energy of the winds which, in turn, drives the ocean circulation. Some of the intercepted solar energy is transformed by photosynthesis into biomass, a large proportion of which is ultimately converted into heat energy by chemical oxidation within the bodies of animals and by the decomposition and burning of vegetable matter. A very small proportion of the photosynthetic process produces organic sediments which may eventually be transformed into fossil fuels. It is estimated that the solar radiation intercepted by the Earth in seven days is equivalent to the heat that would be released by the combustion of all known reserves of fossil fuels on the Earth. The Sun, therefore, is of fundamental importance in the understanding of the uniqueness of the Earth.

The Sun is a main sequence star in the middle stages of its life and was formed 4.6×10^9 years ago. It is composed mainly of hydrogen (75% by mass) and helium (24% by mass); the remaining 1% of the Sun's mass comprises the elements oxygen; nitrogen; carbon; silicon; iron; magnesium and calcium. The emitted energy of the Sun is 3.8×10^{26} W and this energy emission arises from the thermonuclear fusion of hydrogen into helium at temperatures around 1.5×10^{7} K in the core of the Sun.

In the core, the dominant constituent is helium (65% by mass) and the hydrogen content is reduced to 35% by mass as a direct result of its consumption in the fusion reactions. It is estimated that the remaining hydrogen in the Sun's core is sufficient to maintain the Sun at its present luminosity and size for a further 4×10^{9} years. At this stage it is expected that the Sun will expand into a red giant and engulf all of the inner planets of the solar system (i.e. Mercury, Venus, Earth and Mars).

There exists a high-pressure gradient between the core of the Sun and its perimeter, and this is balanced by the gravitational attraction of the mass of the Sun. In the core, the energy released by the thermonuclear reaction is transported by energetic photons but, because of the strong absorption by peripheral gases, most of these photons do not penetrate to the surface. This absorption causes heating in the region outside the core. In contrast, the outer layers of the Sun are continually losing energy by radiative emission into space in all regions of the electromagnetic spectrum. This causes a large temperature gradient to develop between the surface and the inner region of the Sun. This large temperature gradient produces an unstable region and large scale convection currents are set up that transfer heat to the surface of the Sun. The convection currents are visible as the fine grain structure, or granules, in high resolution photos of the Sun's surface. It is thought that the convection currents have a three-tier structure within the Sun. The largest cells, 200×10^{3} km in diameter are close to the core. In the middle tier the convection cells are about 30×10^{3} km in diameter and at the surface they are 1×10^3 km. The latter cells have a depth of 2000 km. In each cell, hot gas is transported towards the cooler surface, whilst the return flow transports cooler gases towards the interior.

Almost all of the solar radiation emitted into space, approximately 99.9%, originates from the visible disc of the Sun, known as the photosphere. The photosphere is the region of the Sun where the density of the solar gas is sufficient to produce and emit a large number of photons, but where the density of the overlying layers of gas is insufficient to absorb the emitted photons. This region of the Sun has a thickness of approximately 500 km but no sharp boundaries can be defined. The radiative spectrum of the Sun, when fitted to a theoretical black body curve, gives a black body temperature of 6000 K, although the effective temperature, deduced from the total energy emitted by the Sun, gives a lower temperature of 5800 K.

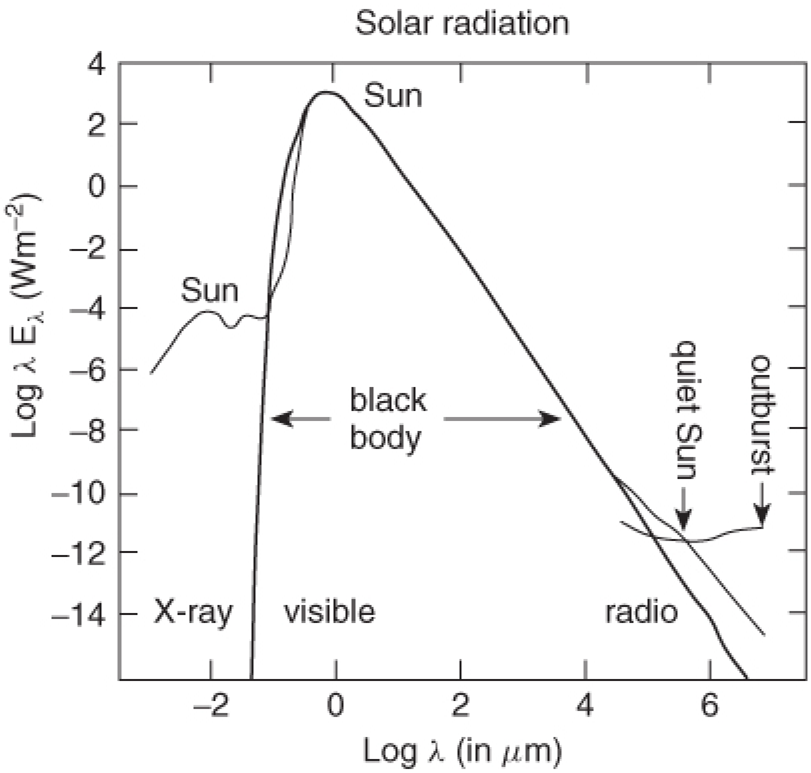
The photosphere is not uniform in temperature. The lower regions of the photosphere have temperatures of 8000 K, whilst the outer regions have temperatures of 4000 K. Furthermore, the convection cells produce horizontal temperature variations of 100 K between the ascending and descending currents of solar gas. Larger convection cells also appear in the photosphere and they have diameters of 30 000 km. They appear to originate from the second tier of convection within the Sun. The appearance of sunspots gives rise to horizontal variations of 2000 K within the photosphere. The inner regions of the sunspots have black body temperatures of 4000 K. Sunspots have diameters of 10 000–150 000 km and they may last for many weeks. It is thought that the 'sunspot' causes a localised suppression of the convection and therefore leads to a reduction in the transfer of heat into the photosphere from the interior. However, although the sunspot features are dramatic, they occupy less than 1% of the Sun's disc and therefore the effect on the luminosity of the Sun is small.

Beyond the photosphere lies the chromosphere where the temperature decreases to a minimum of 4000 K at 2000 km above the photosphere and then increases sharply to a temperature of 10^6 K at a height of 5000 km in the region of the corona. However, because of the low density of the gas in this region, the radiation emitted from the chromosphere and the corona only amount to 0.1% of the total radiation from the Sun.

These different temperature zones of the Sun can be observed in the solar spectrum (Figure 1.1). The visible and infra-red radiation emitted from the photosphere follow reasonably closely the black body curve for a temperature of 5800 K. However, substantial deviations from the theoretical curve occur in the X-ray and radio wavebands, and lesser deviations occur in the ultraviolet spectrum. The high temperature of the corona is responsible for the intense X-ray band, whilst the high radio frequency energy is associated with the solar wind and solar activity. However, the energy in these wavebands is a negligible fraction of the total emitted energy and therefore these very variable regions of the spectrum have little direct influence on the total solar energy received on the Earth. The depletion of energy in the ultraviolet spectrum is the result of emission at a lower temperature than the photosphere and therefore probably originates in the temperature minimum of the lower chromosphere. Recent observations have shown that the ultraviolet energy is not constant and shows considerable variability in the short-wave part of the spectrum amounting to 25% of its average value at 0.15 μm, and 1% at 0.23 μm. Again, the amount of energy in this band is relatively small and contributes less than 0.1% of the total energy. Furthermore, satellite observations of the solar spectrum since 1978 have demonstrated a 0.1%

variation of the solar output over the 11 year sunspot cycle. These variations are rather small when compared to those produced by orbital variations of the Earth around the Sun.

Figure 1.1 Solar spectrum and blackbody curve: energy distribution of the Sun and a black body at 5800 K. Reproduced, with permission, from Allen, C.W., 1958, Quarterly Journal of the Royal Meteorological Society, 84: page 311, figure 3



1.2 Orbital variations in solar radiation

Let S be the total solar output of radiation in all frequencies. At a distance, r, from the centre of the Sun, imagine a sphere of radius r on which the flux of radiation will be the same (assuming the radiation from the Sun is equal in all directions). If the flux of radiation per unit area at a distance

r is given by $Q(r)$, then the total radiation on the imagined sphere is $4\pi r^2 Q(r)$.

In the absence of additional energy sources to the Sun

1.1 $S = 4\pi r^2 Q(r)$

Rearranging:

1.2 $Q(r) = \dfrac{S}{4\pi r^2}$

In practice, the solar radiation cannot be measured at the Sun but it can be measured by satellites above the Earth's atmosphere. Recent determinations of the flux of radiation per unit area, Q, give a value of 1360 W m^{-2}. Given that the Earth is approximately 1.5×10^{11} m away from the Sun, S can be calculated to be 3.8×10^{26} W.

Though S is the true solar constant, in meteorology Q is defined as the solar constant of the Earth. Table 1.1 shows the value of the solar constant obtained for other planets in the solar system. It is noted that the dramatic changes in the solar constant between the Earth and our nearest planetary neighbours, Mars and Venus, merely serve to highlight the uniqueness of the position of the Earth in the solar system. At the radius of Pluto (some 39 Earth-Sun distances), the flux of the radiation from the Sun is less than 1 W m^{-2}.

Table 1.1 Radiative properties of terrestrial planets. Q is the solar irradiance at distance r from the Sun, α is the planetary albedo, T_e is the radiative equilibrium temperature and T_s is the surface temperature

	$r(10^9 m)$	$Q(W\,m^{-2})$	α	$T_e(K)$	$T_s(K)$
Venus	108	2623	0.75	232	760
Earth	150	1360	0.30	255	288
Mars	228	589	0.15	217	227

The radiation incident on a spherical planet is not equal to the solar constant of the planet. The planet intercepts a disc of radiation of area πa^2, where a is the planetary radius, whereas the surface area of the planet is $4\pi a^2$. Hence the solar radiation per unit area on a spherical planet is

1.3 $$\frac{Q\pi a^2}{4\pi a^2} = \frac{Q}{4}$$

The average radiation on the Earth's surface is 340 W m^{-2}. The above discussion assumes the total absence of an atmosphere and that the Earth is a perfect sphere in a spherical orbit.

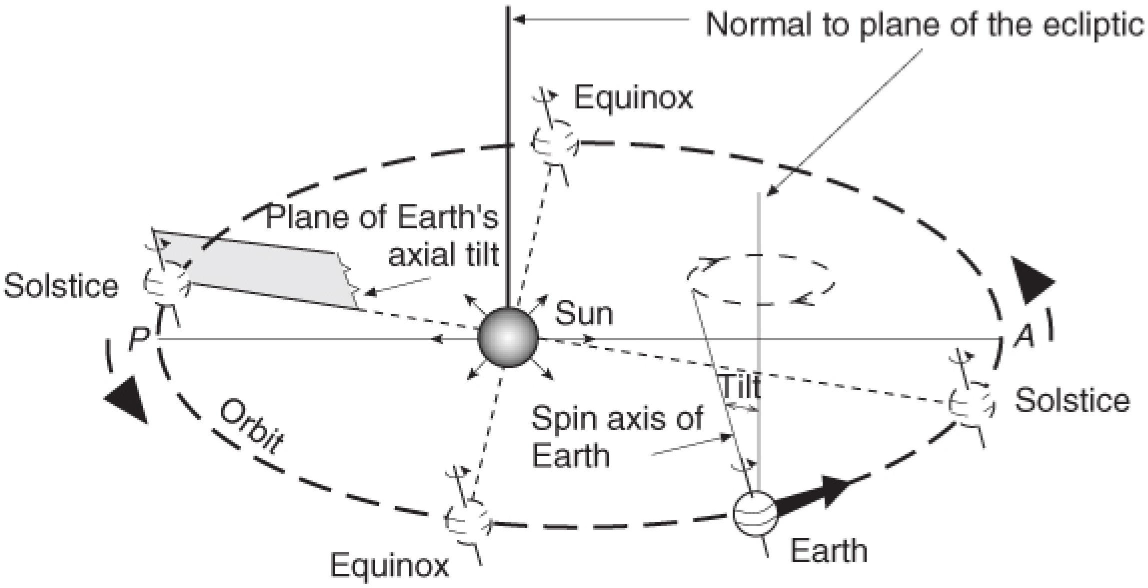
The three geometrical factors which determine the seasonal variation of solar radiation incident on the Earth are shown in Figure 1.2. The Earth revolves around the Sun in an elliptical orbit, being closest to the Sun, i.e. at perihelion, about 4 January and farthest from the Sun, i.e. at aphelion, on 4 July. The eccentricity, represented by the symbol *e*, of the present day orbit is 0.017. At aphelion, it can be shown that

$$r_{aphelion} = (1 + e)\bar{r}$$

where $\bar{r}$ is the mean distance between the Earth and the Sun.

Figure 1.2 Geometry of the Earth–Sun system. The Earth's orbit, the large ellipse with major axis AP and the Sun at one focus, defines the plane of the ecliptic. The plane of the Earth's axial tilt (obliquity) is shown passing through the Sun corresponding to the time of the southern summer solstice. The Earth moves around its orbit in the direction of the solid arrow (period one year) whilst spinning about its axis in the direction shown by the thin curved arrows (period one day). The broken arrows shown opposite the points of aphelion (A) and perihelion (P) indicate the direction of the very slow rotation of the orbit. Reproduced, with permission, from Pittock, A.B. *et al*. eds, 1978, Climate Change and Variability:

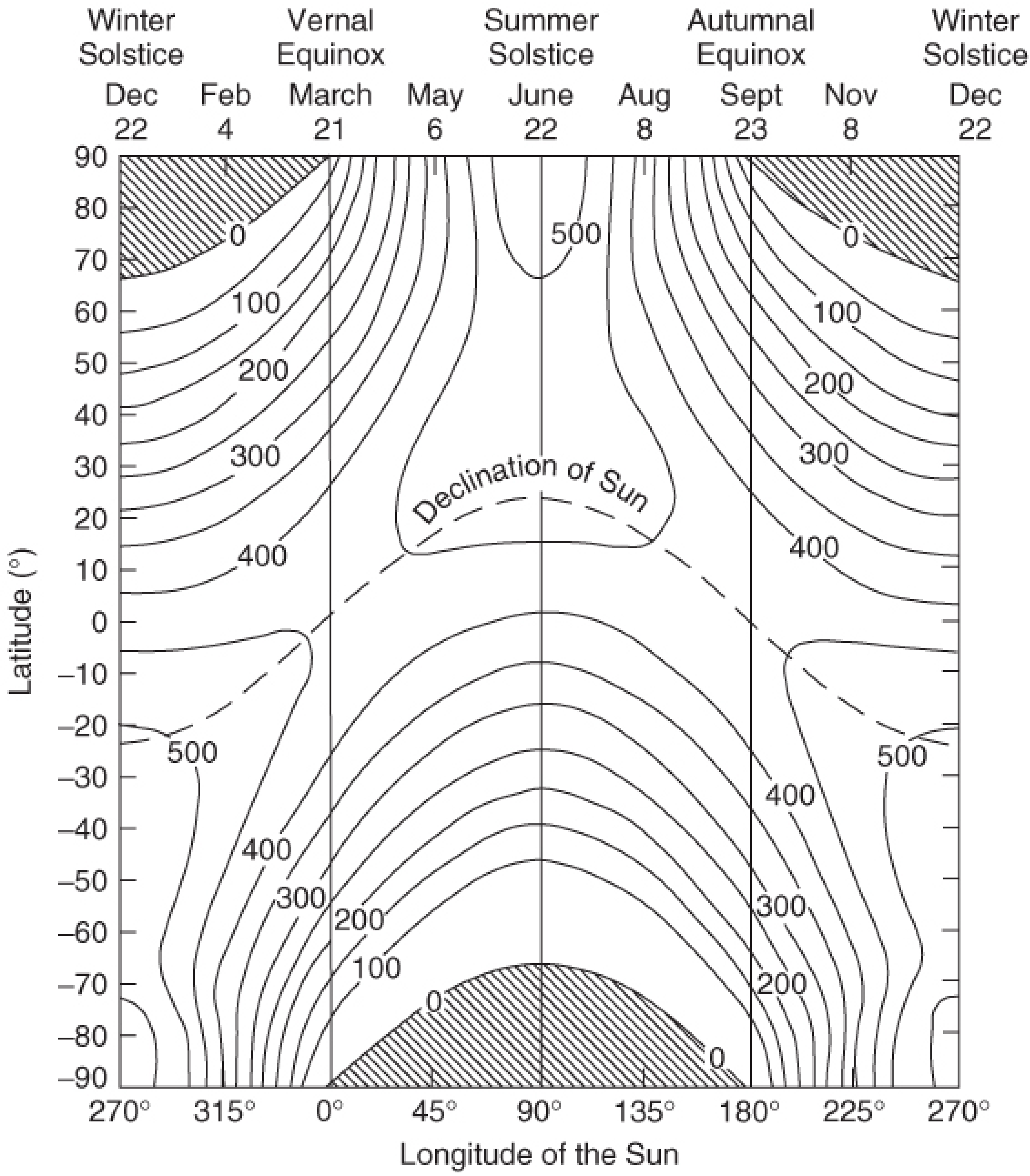
A Southern Perspective, Cambridge University Press: page 10, figure 2.1



As the incident radiation is inversely proportional to the square of the Earth's distance from the Sun, it can also be shown that, at aphelion, the radiation received by the Earth is 3.5% less than the annual average, whilst at perihelion it is 3.5% greater than the annual average. Therefore the total radiation incident on the Earth over the course of one year is independent of the eccentricity of the Earth's orbit. The long-term variation in eccentricity indicates changes of 0.005–0.060 occurring with a period of 100 000 years. This would produce changes of up to 10% in the radiation incident on the surface of the Earth at perihelion and aphelion.

However, the angle of tilt (ε) of the Earth with respect to the plane of rotation of the Earth's orbit, i.e. the obliquity of the ecliptic, is the dominant influence on the seasonal cycle of solar radiation (Figure 1.3). It not only determines the march of the seasons, but it is also important in determining the latitudinal distribution of the climatic zones. At the present time, the angle is 23.5°, which is similar to the obliquity of Mars. It can be shown that the amplitude of the seasonal variation in the solar radiation is directly proportional to the obliquity. If the obliquity were reduced, there would be a reduction in the amplitude of the seasonal solar radiation cycle, and if the obliquity were zero, the seasonal variation would depend solely on the eccentricity of the orbit.

Figure 1.3 Solar radiation in W m^{-2} arriving at the Earth's surface, in the absence of an atmosphere, as a function of latitude and time of year at 2000 A.D. Reproduced, with permission, from Hess, S.L., 1959, Introduction to Theoretical Meteorology, Holt, Rinehart & Winston: page 132, figure 9.1



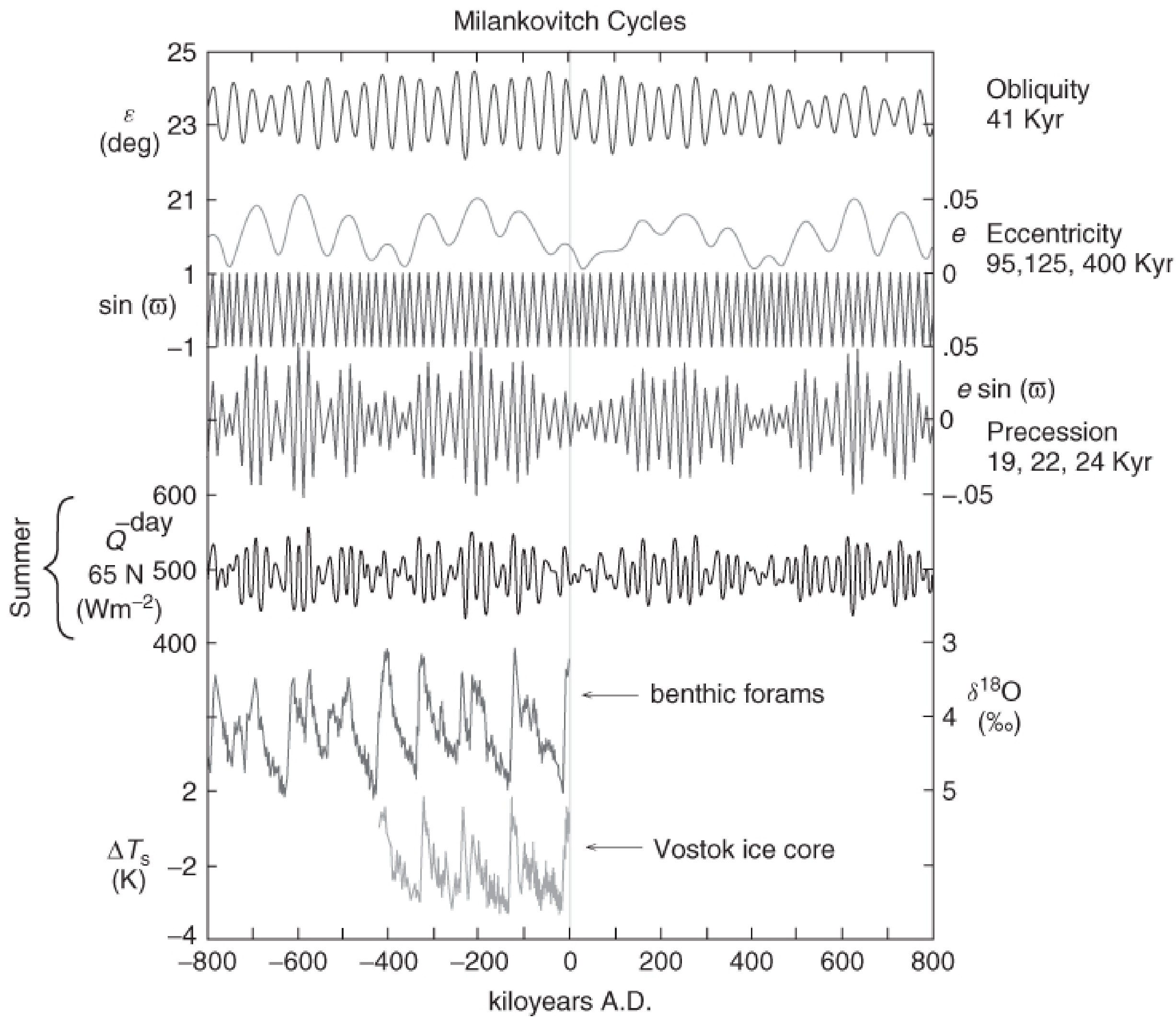
The obliquity has varied between 22° and 24.5° over the past million years and this variation has a total period of 41 000 years. Such variations cannot influence the total radiation intercepted by the Earth, but they will exert an influence on the seasonal cycle.

The third parameter which affects the seasonal cycle is the longitude of the perihelion, measured relative to the vernal equinox. It precesses by 360° in a period of 21 000 years.

Therefore, in about 10 500 years' time, the Earth will be closest to the Sun in July and farthest away in January.

The sensitivity of the global temperature to the seasonal cycle, which arises from ice, cloud and ocean feedback processes, indicates that these changes may be sufficient to initiate long term changes in climate and, in the most extreme cases, ice ages (Figure 1.4).

Figure 1.4 Past and future Milankovitch cycles ε is obliquity (axial tilt), *e* is eccentricity, ϖ is longitude of perihelion. *e* sin(ϖ) is the precession index, which together with obliquity, controls the seasonal cycle of insolation. $\overline{Q}_{\mathrm{day}}$ is the calculated daily-averaged insolation at the top of the atmosphere, on the day of the summer solstice at 65 N latitude. Benthic forams and Vostok ice core show two distinct proxies for past global sea level and temperature, from ocean sediment and Antarctic ice respectively. Vertical gray line is current condition, at 2 ky A.D. See plate section for a colour version of this image



Milankovitch, a Serbian scientist, recognized the relationship between the variations in the Earth's orbit around the Sun and climate change over the last two million years. In particular, he determined the orbital conditions which would lead to the initiation of an ice age over the Northern Hemisphere continents. He reasoned that a reduction in solar radiation during the polar summer would lead to a reduction in summer melting of the snow cover. This, in turn, over many years, would lead to the build up of ice over the continents. The optimum orbital conditions for this reduction in the summer solar radiation are:

(i) That aphelion occurs during the Northern Hemisphere summer.

(ii) That the eccentricity be large, to maximise the Earth–Sun separation at aphelion.

(iii) That the obliquity be small.

These three factors would act to decrease the amplitude of the solar radiation cycle and therefore reduce the solar radiation in summer at high latitudes in the Northern Hemisphere. However, all of these factors would tend to lead to an increase in solar radiation in the Northern Hemisphere winter. Comparison of the orbital parameters with long term temperature records, deduced from the dating of deep ocean sediment cores, indicate that there is a good statistical agreement with the theory.

1.3 Radiative equilibrium temperature

The inner planets of the solar system have one common attribute–the lack of a major source of internal energy. It is, of course, true that there is a steady geothermal flow of energy from the interior of the Earth as a result of radioactive decay in the Earth's core, but this energy flow is less than 0.1 W m^{-2} and can be compared with an average solar heat flux of 340 W m^{-2}. What, then, is the fate of this steady input of solar energy? On average, about 30% is scattered back into space by clouds; snow; ice; atmospheric gases and aerosols, and the land surface, leaving 70% available for the heating of the atmosphere, the ocean and the Earth's surface. However, the annual average of the Earth's temperature has not changed by more than 1 K over the past 100 years. Why, then, have the temperatures of the atmosphere and ocean not increased? The observation that both the temperatures of the atmosphere and the ocean have remained relatively constant implies that energy is being lost from the ocean, the atmosphere and the

Earth's surface at approximately the same rate as it is being supplied by the Sun. The only mechanism by which this heat can be lost is by the emission of electromagnetic radiation from the Earth's atmosphere into space. If it is assumed that the Earth can be represented by a black body, then it is possible to apply Stefan's law to the electromagnetic emission of the Earth. Stefan's law states that the total emission of radiation from a black body over all wavelengths is proportional to the fourth power of the temperature, i.e. $\mathrm{E} = \sigma T^4$, where σ is the Stefan–Boltzmann constant. For the emission by the Earth of an amount of radiation equal to that received from the Sun, there can be defined a radiative equilibrium temperature, T_e.

If $Q/4$ is the energy flux from the Sun and α is the fraction of solar radiation reflected back into space, known as the planetary albedo, then for the Earth's system in thermal equilibrium:

1.4 $$\left(\frac{Q}{4}\right)(1-\alpha) = \sigma T_e^4$$

where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}. By inserting α = 0.3 and $Q/4 = 340$ W m^{-2}, a radiative temperature of 255 K or −18°C can be calculated.

This temperature is lower than might be expected. The mean surface temperature of the Earth is 15°C, or 288 K, and so it is clear that the radiative temperature bears little direct relationship to the observed surface temperature. This is because most of the planetary radiation is emitted by the atmosphere, whilst only a small fraction originates from the surface of the Earth. The temperature of the atmosphere decreases by 6.5 K km^{-1} from the surface to the tropopause, 10 km above the Earth's surface, and therefore the radiative equilibrium temperature corresponds to the temperature at a height of 5 km.

The Wien displacement equation enables the calculation of the wavelength of maximum radiation, $\lambda_{\max}$, and it states that

1.5 $\lambda_{\max} T = 2897\,\mu\mathrm{m}\,\mathrm{K}$

If the radiative temperature, T_e = 255 K, is substituted in this equation, then $\lambda_{\max}$ is calculated to be approximately 11 μm, which lies in the middle part of the infra red spectrum. In this region of the electromagnetic spectrum, water and carbon dioxide have large absorption bands so that all substances containing water are particularly good absorbers of radiation in the middle infra red. As far as emission is concerned, water has an emissivity of 0.97, which means that it emits radiation at the rate of 97% of the theoretical black body value. Hence clouds, which are composed mainly of water droplets, are good infra red emitters. The prevalence of liquid water and water vapour in the Earth's atmosphere therefore leads to the strong absorption and re-emission of radiation. This ability of water to absorb and re-emit radiation back to the Earth's surface results in the higher observed mean surface temperature. If the atmosphere was transparent to the emitted planetary radiation, then the surface temperature would be close to the radiative equilibrium temperature. The temperature of the surface of a planet without an atmosphere, such as Mercury, would be observed to have a surface equilibrium temperature equal to that of the radiative equilibrium temperature. Table 1.1 shows the radiative equilibrium temperatures for Mars and Venus, as well as their surface temperatures. The surface temperatures are higher than the radiative temperatures. On Mars the atmospheric mass is smaller than that of Earth by two orders of magnitude and therefore, though carbon dioxide absorbs and re-emits planetary radiation back to the surface, a surface warming of only 19 K is produced. However, on Venus the surface temperature of 760 K is sufficient to melt lead, in spite of the fact that the radiative equilibrium temperature is less than that of the Earth. This low radiative equilibrium temperature is caused by the reflection of 77% of the incident solar radiation back into space by the omnipresent clouds, which are not composed of water droplets as they are on Earth. Therefore, although the planet receives less net solar radiation than the Earth, it has a surface temperature 472 K higher. This is the result of the massive carbon dioxide atmosphere, which absorbs virtually all of the radiation emitted by the surface and re-emits it back to the surface. Furthermore, it is known that clouds of sulphuric acid also enhance this warming effect.

The ability of an atmosphere to maintain a surface temperature above the radiative equilibrium temperature is commonly known as the ‘greenhouse effect’.

It is clear that, although the distance from the Sun determines the energy incident on an atmosphere, the mass and the constituents of that atmosphere are also important factors in the determination of the surface temperature of the planet.

1.4 Thermal inertia of the atmosphere

The thermal inertia of the atmosphere gives an indication of how quickly the atmosphere would respond to variations in solar radiation and it is therefore of importance in the understanding of climatic change. Consider an atmosphere having a mass M, per unit area, and a specific heat at constant pressure, C_p. The thermal inertia of the atmosphere is MC_p.

Initially, the atmosphere is in thermal equilibrium and therefore the solar radiation absorbed by the atmosphere is