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Introduction

The purpose of this introduction is to develop a broad perspective within which to view ice. Accordingly, the chapter deals with origin, evolution, incidence and impact. It begins with ice in an astronomical context and an astronomical time scale, bringing us gradually to the point when the Earth attained the form it has today. Then follows a brief outline of the variable presence of ice, particularly on a large scale, in an attempt to reveal its two opposite faces: the great beauty and the immense danger. The chapter ends with some of the recorded responses of mankind to ice.

1.1 Ice in the heavens

It is now generally accepted by astronomers that the Universe evolved from a cataclysmic explosion which took place at least 10^{10} years ago. Ever since that moment, the energy and matter so released have been expanding radially outwards, eventually cooling at an asymptotic rate which, according to the tenets of thermodynamics and relativity theory, is expressed in the relation

$$T \propto 1/t^{\frac{2}{3}} \qquad (1.1)$$

where T is the absolute temperature and t is the 'absolute' time. At present, the temperature in deep space is about 2.7 K thus implying that for the first 10^7 years the magnitude was in excess of 273 K: i.e., for all but the first 0.1% of its existence the Universe has been cold enough to tolerate the formation of ice, assuming that H_2O molecules were available in sufficient numbers. (Strictly speaking $T \propto t^{\frac{1}{2}}$ during the first 10^6 years but the conclusion remains the same.)

The primordial medium in the early Universe consisted largely of the first two elements, hydrogen and helium, produced from nucleosynthesis, but it was not until the medium had given rise to galactic formations in which stars were born, evolved, and died that the helium nuclei began

Table 1.1. *Materials of the Universe (following Allen (1973) and Illingworth (1985))*

Relative cosmic abundances (by mass)			
H	7.3×10^{-1}	Na	4×10^{-5}
He	2.5×10^{-1}	Mg	5×10^{-4}
Li	4×10^{-8}	Al	6×10^{-5}
Be	8×10^{-10}	Si	7×10^{-4}
B	6×10^{-9}	P	5×10^{-6}
C	3.0×10^{-3}	S	4×10^{-4}
N	1.0×10^{-3}	Cl	3×10^{-6}
O	8.0×10^{-3}	A	7×10^{-5}
F	5×10^{-7}	K	2×10^{-6}
Ne	1.0×10^{-3}	Ca	4×10^{-5}
Some components of the interstellar medium			
OH^-		CN	
H_2O		HCN	
CO		NH_3	
H_2CO		HN_2^+	
CH_3OH		CH_4	

interacting to produce other elements, notably ^{12}C and ^{16}O. Table 1.1 lists some of the elements created and then distributed by supernova explosions and stellar winds (Allen, 1973; Illingworth, 1985). Also listed in Table 1.1 are some of the molecules and ions subsequently formed as the interstellar medium cooled. Cosmic dust is an important component of the interstellar medium. It consists of carbon, silicate and iron particles which swarm into dense clouds, at which point they are observed to possess icy mantles, the most primitive and most widespread form of glaciation in the Universe.

After gravity had generated the galaxy, and thence a variety of stars, the gas and dust remaining in the vicinity of the Sun gradually transformed itself by accretion into the solar system we know today. In the condensation process, the materials with the highest evaporation temperatures (refractories) formed first and may have grown into fairly large masses before the later volatile components formed grains; turbulence kept them mixed. The mechanism by which the pre-planetary grains grew into planetesimals and eventually coalesced into the present planets is unknown, but it appears to have led to planetary structures in which refractories were concentrated in the core while volatiles remained closer to the surface.

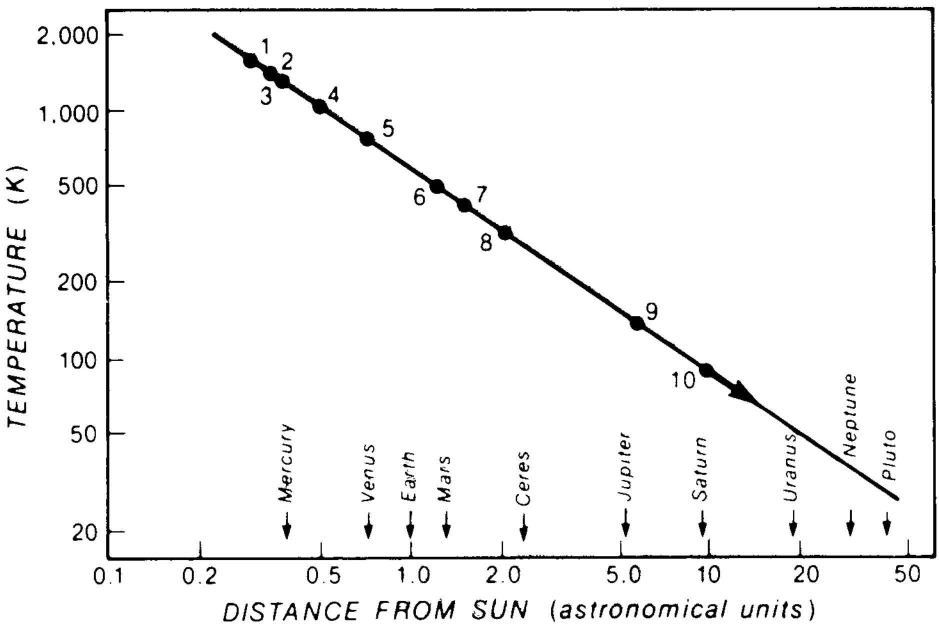

Fig. 1.1. Indicated in this diagram are the temperatures and locations at which major planetary constituents would be expected to condense from the primordial solar nebula: 1, refractory minerals like the oxides of calcium, aluminium, and titanium, and rare metals like tungsten and osmium; 2, common metals like iron, nickel, cobalt, and their alloys; 3, magnesium-rich silicates; 4, alkali feldspars (silicates rich in sodium and potassium); 5, iron sulphide; 6, the lowest temperature at which unoxidized iron metal can exist; 7, hydrated minerals rich in calcium; 8, hydrated minerals rich in iron and magnesium; 9, water ice; and 10, other ices, (following Lewis (1982)).

Important to the understanding of planetary composition is the relation between the condensation temperatures of various constituents and the corresponding distance from the sun (Lewis, 1982). Fig. 1.1 illustrates this relation from which it is evident that structural planetary ice in any abundance may not be expected within the orbit of Jupiter. Equally important, at least from the point of view of the terrestrial planets, is the development and evolution of an atmosphere (Pollack, 1982a). It seems likely that outgassing of volatile-laden minerals was the primary atmospheric source, although it is also possible that the solar nebula, the solar wind and collision with volatile rich comets may have made contributions. Initially, the gases vented were chiefly water vapour, carbon dioxide, carbon monoxide, hydrogen and nitrogen, as Table 1.1 might suggest, but their continued participation in the energy exchange processes at the surface of the planet gradually produced substantial changes which varied from planet to

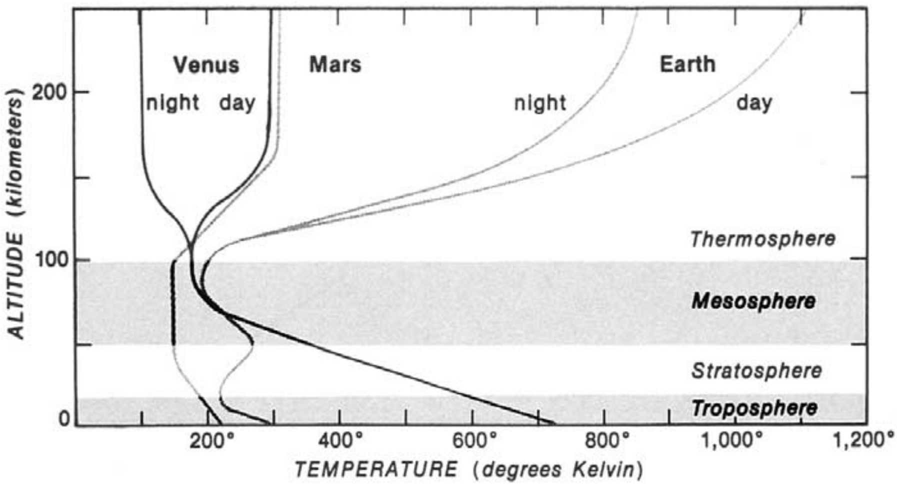

Fig. 1.2. A comparison of temperature variations with altitude for Venus, Earth, and Mars. The day–night pairs of curves show the strong diurnal cycle in the upper atmospheres of Earth and Venus. Also indicated are the names given to the regions within the Earth's atmosphere (following Pollack (1982a)).

planet. Volcanism, the loss of hydrogen to space, the accumulation of inert nitrogen, the formation and condensation of water vapour and the chemical reactions of carbon dioxide and carbon monoxide with water vapour and rock, all led to atmospheric evolution during approximately 5×10^9 years of planetary existence.

The atmospheres of the Earth and its two nearest neighbours currently contain many gases in common but their proportions differ (Pollack, 1982a). Perhaps not surprisingly they all contain H_2O, though in very small amounts: about 1% for Earth, and much less for Mars and Venus. Fig. 1.2 shows the variation of temperature with altitude for these planets, and makes it abundantly clear that H_2O will not remain in vapour form at every altitude; this is particularly true of the low altitudes on Mars and Earth. Some of the condensed water vapour is, or was, present as water but much of it exists as ice, especially in the polar regions of these planets. Fig. 1.3 shows the spiral form of Mars' north polar ice cap on which wind erosion and vapour deposition appear to have alternated in the production of layers of ice and particulates. The Martian regolith, the surface soil and rock, is also a likely location for condensed water vapour, probably in the form of extensive permafrost; water may have flowed in the past, and may still exist beneath and within the permafrost (Masursky, 1982; Krass, 1984).

Further out in the solar system are Jupiter and Saturn which, although

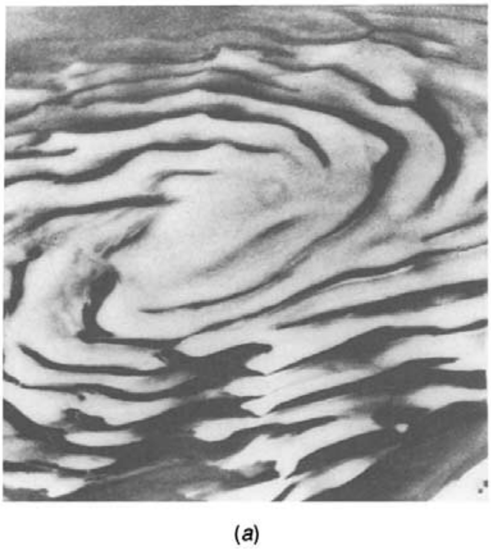

Fig. 1.3. From its high-inclination orbit, the Viking 2 orbiter photographed the involved spiral of Mars' north polar water-ice cap seen in (a). Visible in (b) is a cliff in the Martian north polar cap; strikingly layered deposits of dust and ice have been eroded, overlain by fresher deposits of ice, then eroded again (following Pollack (1982a)).

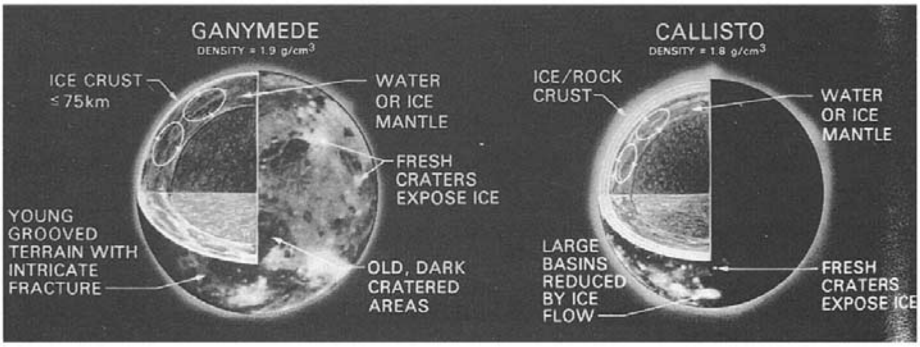

Fig. 1.4. These schematic illustrations portray the satellite interior as presently understood (following Johnson (1982)).

possessing no ice themselves, are in close proximity to it (Johnson, 1982; Krass, 1984). Two of the moons of Jupiter, Ganymede and Callistro, are not only covered in ice but also have a deep mantle of ice or water: over one-third of their volume is H_2O. As Fig. 1.4 indicates, an ice/rock crust has developed above the mantle as a result of meteoric impact over an extended period of time. Fig. 1.5 shows a possible sequence of events in

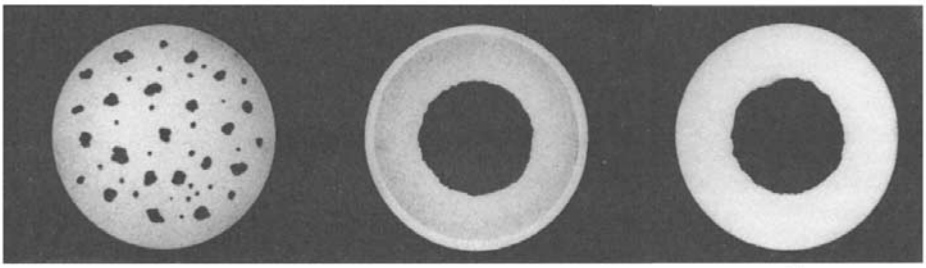

Fig. 1.5. A possible sequence in the evolution of Titan's interior. Soon after condensing from the nebula surrounding Saturn, the satellite's heterogeneous mixture of ices and silicates (*a*) begins to segregate, as heat created during formation mobilizes the interior. Rocky material sinks to the centre, and water, ammonia, and methane rise to the top; at first, residual heat keeps all but the outermost portion liquid (*b*). Heat loss from the mantle through the ice crust soon freezes the entire mixture (*c*), probably within the first billion years of Titan's existence (following Pollack, (1982b)).

the formation of Titan, Saturn's largest moon (Pollack, 1982b). The density of the ice crust may be expected to increase with depth, so much so that ices I, II, V and VI[1] are likely to exist in concentric rings beneath the surface. Perhaps more surprising is the presence of ice in 'snowballs' as a major constituent in the A and B rings surrounding Saturn (Burns, 1982).

Near the outer edge of the solar system are the planets Neptune and Uranus which also possess rocky cores surrounded by 'ice' mantles; they are covered in a 'crust' of gravitationally compressed hydrogen and helium. The state of the H_2O in these mantles is not yet known but it is believed to be a highly-compressed, ionized fluid capable of thermal convection and therefore capable of generating a magnetic field. Icy worlds such as these are common in the outer solar system, as evidenced by the planet Pluto and the moons of Uranus (Morrison and Cruikshank, 1982). The Voyager satellite explorations have revealed iced surfaces which are not only pitted by meteoric impact but are still in the process of geologic re-surfacing, even by water volcanoes.

Perhaps the most spectacular icy bodies in the solar system are the comets of which there are well over 500 (Brandt, 1982). They are best known for their long tails of plasma or dust, but their head, or coma, which consists of a sphere of gas and dust often 10^5–10^6 km in radius, contains a nucleus. This nucleus, which is believed to be the source of all cometary gas and dust, is composed mainly of ice, as suggested in Fig. 1.6. As the Sun is approached, heating of the nucleus establishes a sublimation

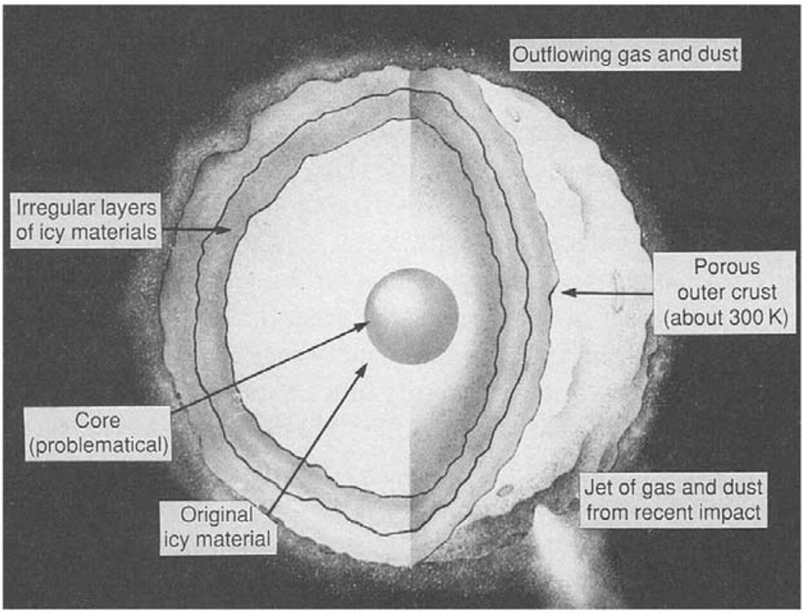

Fig. 1.6. Fred Whipple's 'icy conglomerate' nucleus model, as extended by Armand Delsemme (following Brandt (1982)).

process just below the accumulated dust of the crust, thereby generating the coma and ultimately the tail. Since H_2O is believed to be the principal ingredient of the nucleus it is estimated that the sublimating surface, which may have a radius of 10^2–10^4 m, must have a temperature of about 215 K when it is near the Earth's orbit.

1.2 Ice ages

An elementary heat balance on any body in the solar system reveals that

$$T_b = T_s \left(\frac{R_s}{2R_b}\right)^{\frac{1}{2}} \tag{1.2}$$

where T_b, T_s are the uniform[2] surface temperatures of the body and the Sun, respectively, and R_b, R_s are the distances of the body and the Sun's surface, respectively, from the centre of the Sun. This simple expression indicates that the Earth's average equilibrium temperature should be about 280 K, which is a surprisingly good estimate carrying with it the implication that water should be the prevalent form of H_2O on this planet. Such a prediction is too coarse to accommodate the spatial effects of geometry and atmosphere and the transient effects of spin, orbit and axis tilt, but it does lead naturally to the question of what would happen to the huge amounts of planetary water should the surface temperature over substantial regions of the planet ever fall a mere 10 K below the average.

Everyone is familiar with diurnal and seasonal variations in temperature and the freeze–thaw cycles which they may induce. Less familiar, perhaps, are the precise details of the Earth's spinning and orbital movements and their fluctuating effect on climate; yet it is just such astronomical periodicities which offer the best explanation for the substantial alterations in ice cover which have occurred over the past 10^9 years and, in particular, during the last million years. In the light of such time scales it is sobering to realize that the astronomical theory of ice ages has been formulated only during the past 150 years (Croll, 1875; Milankovitch, 1941; Hays, Imbrie and Schackleton, 1976).

Equation (1.2) suggests that eccentricity in the Earth's orbit could produce annual variations in the equilibrium temperature, at least near the surface (a period of one year is not long enough to permit substantial alterations in the Earth's bulk temperature), but it is not clear how these might lead to a longer term change. Yet climatic records of the past 500 000 years indicate a close correlation between climate and eccentricity, measured as the interfocal distance divided by the major axis (Hays *et al.*, 1976). It thus appears that the influence of other bodies in the solar system produces a cyclic variation in eccentricity, the amplitude being about 6% and the period being of the order of 10^5 years, but the precise mechanism that fosters the widespread growth of ice remains uncertain.

Also important is the Earth's spin or, more precisely, the axis about which the spinning occurs. If this axis lay normal to the ecliptic plane i.e., the plane in which the Earth rotates about the Sun, its daily effect would be periodic and its seasonal effect would be absent. The fact that the axis is currently tilted about 23.5° from the normal to the ecliptic creates differential heating in relation to the plane in which the tilt takes place. At the two orbital positions where the plane is intersected by the Sun, the solstices[3], the differential is greatest: days are shorter and colder at the pole further from the Sun. The solstice plane does not coincide with the major axis of the orbit and is currently displaced from it by about 13 days.

The seasonal effect of axis tilt is plainly evident each year; it is in fact greater than the annual effect of eccentricity (currently about 1%). Observations of tilt reveal that it has not remained constant over the years; thus other bodies in the solar system once again make their presence felt (Berger, 1977), by altering the amplitude of the axis tilt and by rotating the axis about the normal to the ecliptic. The first of these cyclic effects is a

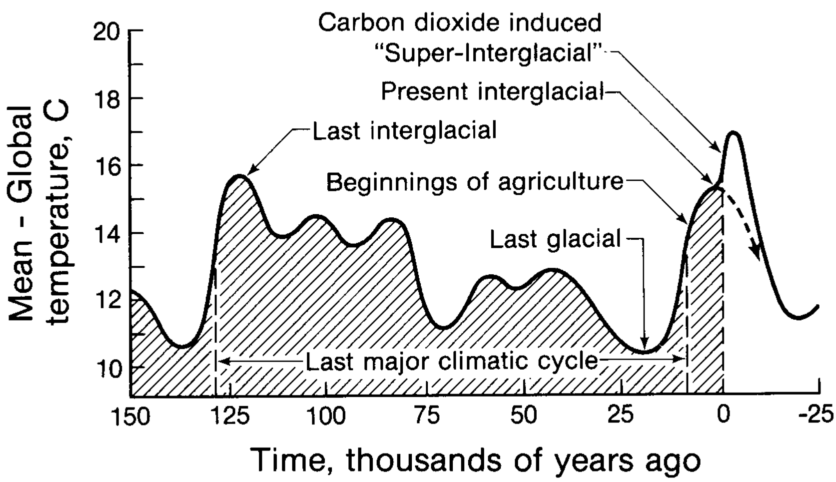

Fig. 1.7. Past and future climate. According to the astronomical theory of ice ages, the natural course of future climate (shown by the dashed line) would be a cooling trend leading to full glacial conditions 23 000 years from now. The warming effect of carbon dioxide, however, may well interpose a 'superinterglacial.' The next ice age would be delayed until the warming had run its course, perhaps 2000 years from now (following Mitchell (1977)).

variation of about 1.5° over a period of approximately 42 000 years. The second, the precession, has a period of approximately 23 000 years (Hays *et al.*, 1976).

Evidently movements elsewhere in the solar system have a predictable, if complex, effect on the density of the radiative flux incident at each point on the Earth's surface, but it is clear that although the radiative flux may trigger climatic change, and will continue to play an important part in it, the climate itself is not likely to respond passively. With respect to water in particular, alterations in the heat balance, locally and globally, lead to variations in circulation and evaporation, and these in turn will combine with altered atmospheric temperatures to vary winds and precipitation rates. The precipitation of snow with its high albedo alters the radiative balance yet further and thus augments the very cooling effect which produced the snow. Such dynamic, interactive effects may be seen every year and it is not difficult to understand how the annual growth and decay of massive planetary ice could shift its balance in response to astronomical perturbations. Fig. 1.7 uses the Earth's mean global temperature to reflect climatic change over the past 1.5×10^5 years (Mitchell, 1977) and shows how superposition of the three principal disturbances produces periodic glacial conditions.

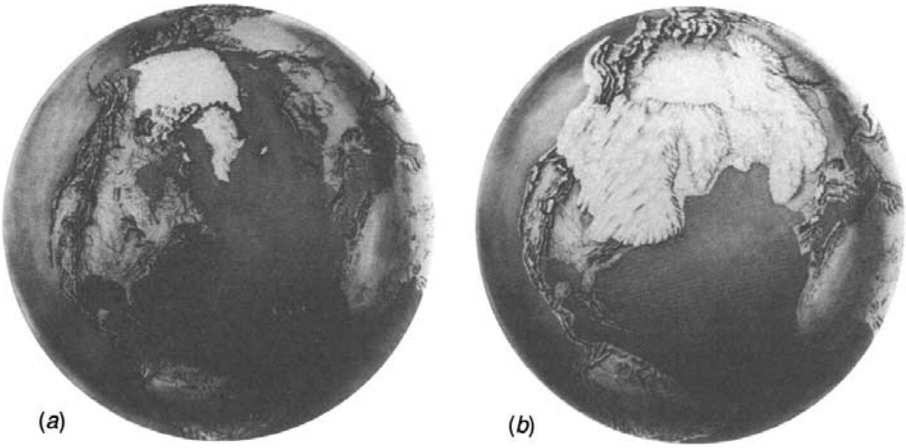

Fig. 1.8. Earth today during (*a*) a hot northern summer and (*b*) a summer of the last ice age. Twenty thousand years ago, great ice sheets covered parts of North America, Europe, and Asia; surface waters of the arctic and parts of the North Atlantic Oceans were frozen; and the sea level was 350 ft lower than it is today. Many parts of the continental shelf, including a corridor between Asia and North America, became dry land. (Drawing by Anastasia Sotiropoulos, based on information compiled by George Denton and other members of the CLIMAP project.) (Following Imbrie and Imbrie (1979).)

During most of the Earth's 5 billion years of existence the astronomical theory of ice ages may not apply because of the enormous structural changes which have occurred in our planet. There is, however, some geological evidence of glacial ages during the last billion years (Imbrie and Imbrie, 1979). These evidently occurred 250–320 million years ago, in the Permo-Carboniferous period of the Paleozoic era, and 600–800 million years ago in the Pre-Cambrian era; the present (late Cenozoic) glacial age began some 10 million years ago. The best current explanation of these glacial ages relies on the theory of continental drift from which it appears that only during certain geological periods has there been a substantial portion of the Earth's land surface located near the poles (Imbrie and Imbrie, 1979). Then, as now, astronomical variations have a greater effect on climate which, as mentioned earlier, may be expected to respond in a non-linear manner, particularly at high latitudes and high elevations. During the Permo-Carboniferous glacial age a huge section of the Earth's surface was covered by the supercontinent of Gondwana, whose southern tip included the South Pole. It was then that glaciation occurred in what are now South America, Africa, India, Australia and Antarctica. The withdrawal of the substantial land mass from the South Pole brought an