Ice Ages

Periodic Ice Coverings on the Earth

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Introduction

On July 24, 1837, Louis Agassiz, President of the Swiss Society of Natural Sciences startled most scientists by declaring that the earth was in the grip of an ice age in the distant past. Agassiz argued that large parts of North America, Great Britain, Denmark, Germany, Poland, Switzerland and Russia were once covered with ice that was at least one kilometer thick. These large ice sheets moved and sculpted wonderful landscapes in many parts of the world. His conclusions were based on the presence of scratches on rocks and the existence of some boulders (called 'erratics') in the Alps far away from their places of origin. Initially, most scientists did not accept the idea that the earth was gripped by ice ages in the distant past. In the 19th century, most scientists believed that the 'erratics' were transported over large distances by huge floods. The huge floods were presumed to be similar to those mentioned in the Bible. Louis Agassiz being a brilliant orator and writer was slowly able to convince many scientists that ice ages did occur in the past.

Theories of Ice Ages

In 1842, the French mathematician Joseph Ademar suggested that the precession of the earth's orbit caused ice ages. The precession of the earth's orbit leads to changes in the time of the year at which the earth is nearest to the sun. Since the earth's orbit around the sun is not a circle but an ellipse, the earth is nearest to the sun at some time and farthest at some other time. At present, the earth is nearest to the sun in December and farthest in June. This makes the winters less severe in the northern hemisphere than in the southern hemisphere. About 11000 years ago, the earth was nearest to the sun in June (see *Figure* 1). About 22,000

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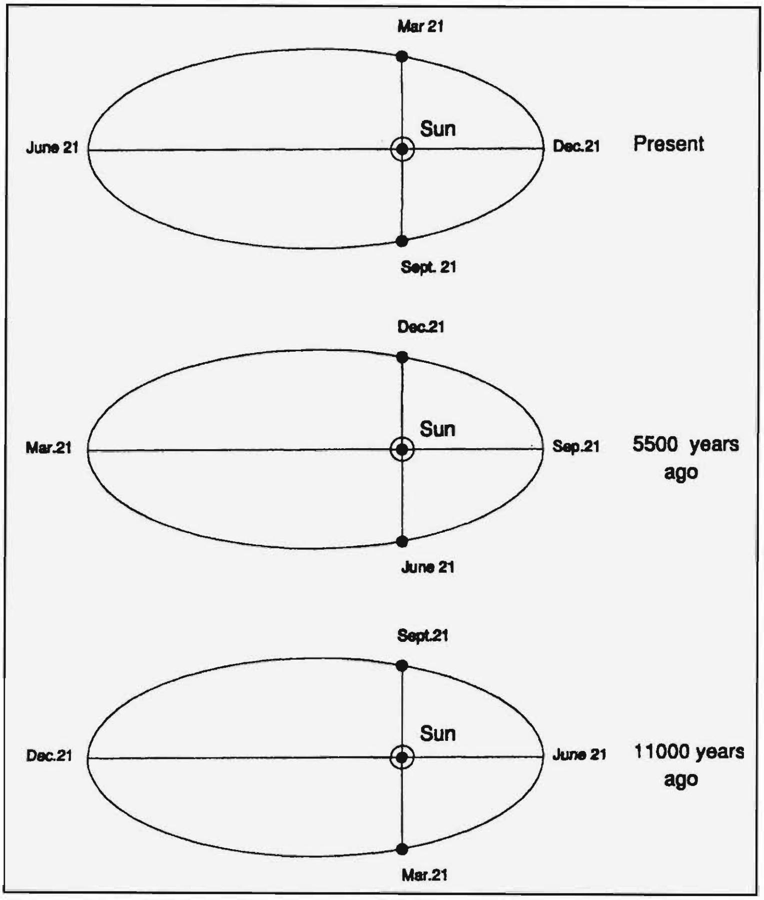

Figure 1. Precession of equinoxes – the time of the year during which the earth is nearest to the sun has varied with a period of 22,000 years. The earth is nearest to the sun in December now but was nearest to the sun in June 11,000 years ago.

years ago the earth was again nearest to the sun in December. Thus, the precession of the earth's orbit fluctuates with a period of 22000 years.

In 1864, James Croll, a janitor in the Adersonian College in Glasgow, proposed that variation in the eccentricity of the earth's orbit was also important for triggering of ice ages. The eccentricity of the earth's orbit around the sun varies between 0.0005 and 0.0607 with period around 1,00,000 years (see *Figure* 2). The eccentricity of the orbit is defined as $(a^2–b^2)/b^2$ where a and b are the major and minor axes of the ellipse. Croll realized that the variations in eccentricity as well as precession could be important for the onset of ice ages. The predictions made by him are shown in *Figure* 3. Note that according to

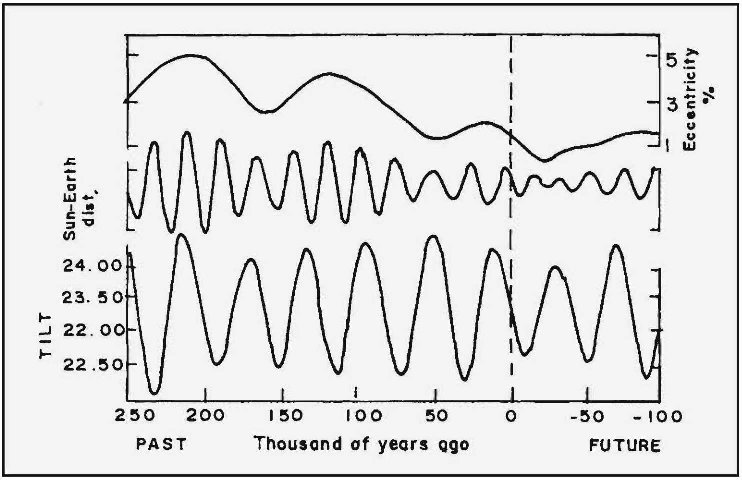

Figure 2. The changes in eccentricity, earth-sun distance in June and the tilt during the past 250, 000 years and the next 1,00,000 years.

Croll's theory, the ice ages alternate between the northern and southern hemispheres. In the 19th century, the observations were not sufficient to either confirm or falsify Croll's hypothesis. James Croll was also the first person to highlight the importance of the high reflectivity of the ice sheets. He suggested that the earth absorbed less solar radiation when the ice sheets expanded. Hence, this leads to further expansion of the ice sheets. These kinds of interactions are called *feedbacks* in modern terminology. The interaction between the increase in ice extent and the increased reflection of solar radiation is known as the *ice-albedo feedback*. This is a positive feedback because the initial increase in ice content is further amplified by high reflectivity (i.e., high albedo) of the ice sheet.

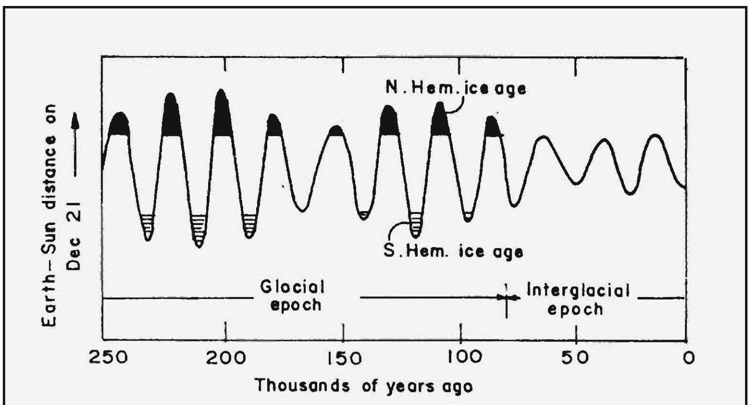

Figure 3. Croll's theory of ice ages based on the earth-sun distance in December during the past 250000 years. Note that this theory predicts that ice ages will occur alternately in the two hemispheres. According to Croll, ice ages occur in the northern hemisphere when the earth-sun distance in winter exceeds a critical value.

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In the 20th century, the most ardent advocate of the astronomical theory of ice ages was the Yugoslav astronomer Milutin Milankovitch. He argued that the changes in eccentricity and precession of the earth's orbit and the tilt of the earth's axis of rotation were important for the periodic appearance of the ice ages. The axis of the rotation of the earth is tilted to the plane of the earth's orbit around the sun. This tilt has varied between 22 degrees and 24.5 degrees. The present value is 23.4 degrees (see *Figure* 2). When the tilt is high, there will be more accumulation of snow in the continents during the winter and less melting during the summer. The tilt of the earth's axis of rotation fluctuates with a period around 41,000 years. Milankovitch argued that when summers are cool and winters are mild the ice sheets in the northern continents grow because of more snowfall in winter and lesser melting of ice in the summer and vice versa. The variation in the earth-sun geometry changes solar radiation incident at the surface. Milankovitch showed that the changes in the eccentricity of the earth's orbit around the sun, the tilt and orientation of its spin axis changed the amount of solar radiation incident on the ice sheets in summer by about 20%. These changes accumulate gradually and hence can lead to accumulation (or depletion) of ice sheets over thousands of years.

The comprehensive hypothesis proposed by Milankovitch could not be tested easily because an accurate method of dating was not available until recently. In the last three decades, there have been tremendous improvements in our ability to date past events by the use of radioactive isotopes. The cosmic rays impinging on the earth create C^{14}, a radioactive isotope of carbon. All the living organisms imbibe this radioactive carbon continuously during their lifetime. When the organism dies, the radioactive carbon within the organism decays and hence the fraction of radioactive carbon remaining can be used to estimate when the organism died. This method is useful to estimate the dates of past climatic events if they occurred in the past 75,000 years. Using thorium-uranium or potassium-argon

Box 1.

How do scientists know when the ice ages occurred in the past? Scientists must infer the past climate from a variety of proxy evidence. Ice cores provide a unique glimpse into the past climate. One of the popular proxy methods is to calculate the ratio of the two isotopes of oxygen. The ratio of O^{18} to O^{16} in the water found in the ice core could be used to infer the existence of an ice age. Since O^{16} is lighter than O^{18}, more O^{16} leaves the ocean during evaporation of water from the ocean. When this water vapor falls as snow or ice it contains more O^{16} than O^{18}. Hence, we should expect that the water in the oceans will be depleted in O^{16} (or enriched in O^{18}) and the ice will be enriched in O^{16} (or depleted in O^{18}) during the ice ages. During ice ages, the sea level falls substantially because a large amount of water is locked up in ice sheets. We should expect, therefore, that there should be a strong correlation between the fluctuations in sea level and the fluctuations in the ratio of O^{18} / O^{16} obtained from ice cores or the sediments from the bottom of the ocean. The sediments that accumulate at the bottom of the ocean contain microfossils such as Foraminifera and Radiolaria. These microfossils have a shell of calcium carbonate. The oxygen in the calcium carbonate was derived from the water in the oceans. Hence the O^{18} / O^{16} ratio in the calcium carbonate provides a measure of the O^{18} / O^{16} ratio in the ancient seas. There is a strong correlation between the fluctuations in the sea level in New Guinea and the fluctuations in O^{18} / O^{16} ratio in Foraminifera in the Indian ocean cores (see *Figure* 4).

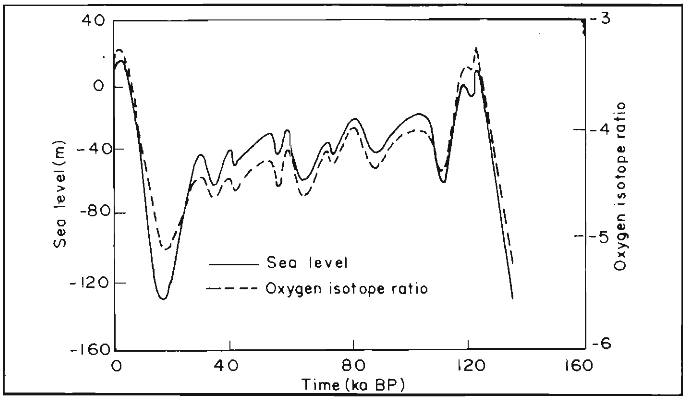

Figure 4. The changes in sea level in New Guinea compared with the O^{18} /O^{16} ratio in the ocean sediments. The variations in sea level are a direct measure of the changes in global ice volume.

radioactive dating can date the events that occurred more than 75,000 years ago.

Observed Climate Variability

In 1976, James D Hays and his collaborators looked at the ratio of O^{18} to O^{16} in the calcium carbonate shells of planktonic organisms called foraminifera in the Indian Ocean (see *Box* 1). The foraminifera were extracted from sediment cores at the bottom of the Indian Ocean. The amplitude of fluctuation of the ratio of O^{18} to O^{16} is a measure of the amplitude of the climatic

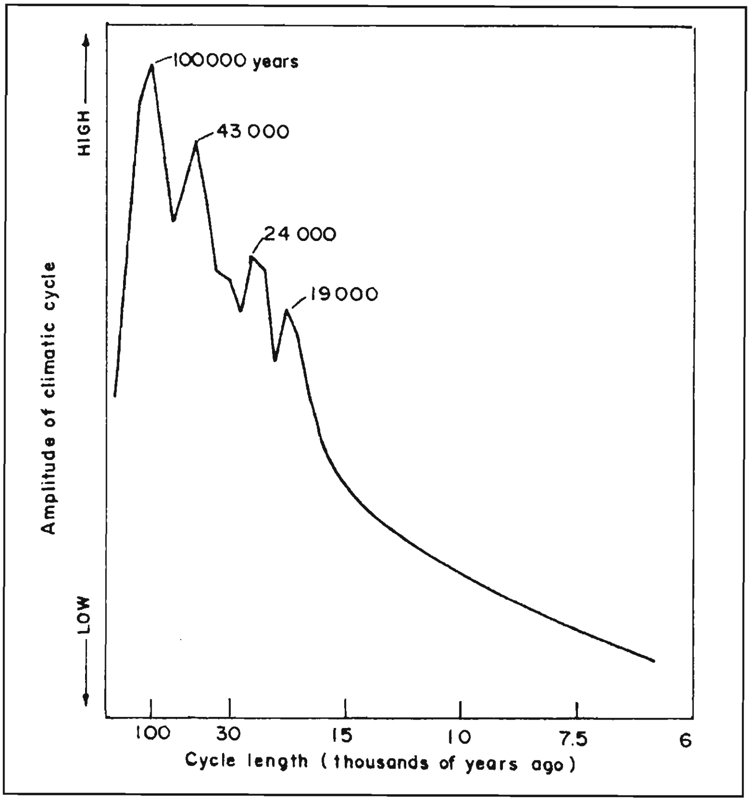

Figure 5 The amplitude of the climatic cycle obtained from the sediments in the Indian ocean.

cycle during the past. The spectral analysis of the data revealed that there were several distinct peaks. These peaks have periods around 1,00,000, 43,000, 24,000 and 19,000 years (*Figure* 5). The eccentricity of the earth's orbit around the sun varies with period around 1,00,000 years. The tilt of the earth's orbit varies with a period around 43,000 years. The precession of the earth's orbit varies with a period around 22,000 years. Hence Hays and his collaborators found that the earth's climate fluctuates with periods that are consistent with the astronomical theory of ice ages proposed by Milankovitch. They concluded therefore that fluctuations in the earth-sun geometry were the pacemaker of the ice ages.

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There are, however, some serious problems with the astronomical theory of ice ages. The ice cores and ocean sediment cores indicate that the largest amplitude of the climate fluctuation occurred with a period around 1,00,000 years. The solar energy incident in the polar regions varies periodically. The largest amplitude of this variation occurs with the period around 20,000 years and not 1,00,000 years. Why the amplitude of the observed climate cycle should be the largest around 1,00,000 years and not 20,000 years has not been fully resolved so far. The solar radiation incident on the ice sheets shows smooth and cyclical variation but the growth and decay of the ice sheets has not been smooth. The ice sheets grow slowly over a period of 1,00,000 years but crash in a few thousand years. A number of new theories have been proposed to explain this paradox.

Several mechanisms have been proposed for the episodic growth and collapse of ice sheets. One of the mechanisms proposed is the effect of the weight of ice on the underlying rock. As the weight of the ice increases, the underlying rock becomes ductile and flows. The sinking of the bedrock causes the elevation of the ice sheet to decrease. When the elevation of the ice sheet is lowered it encounters warmer air and this causes the rapid melting of the ice sheet. Note that this mechanism cannot be invoked for sea ice. Some other scientists have argued that large volcanic eruptions once every 1,00,000 years may trigger ice ages. There is insufficient evidence regarding past volcanic eruptions and hence the above theory cannot be verified.

The Role of the Oceans

Most of the ice age theories proposed in the 19th and 20th centuries did not attribute any role to the oceans. James Croll had hinted that ocean circulation may play a role but did not pursue this matter further. Oceans should have a large impact on global climate because the mass of the ocean is large. This coupled with the high specific heat of water implies that the ocean has a large thermal inertia. This thermal inertia can delay changes that can occur in the global climate in response to changes in solar radiation. Moreover, ocean is the source of most of the snowfall and rainfall in the continental regions. A small increase in ocean temperature implies a large increase in evaporation rates and hence a large increase in rainfall rates over

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the continents. The extent of ice in continental regions can increase if and only if the amount of snowfall in winter exceeds the amount of ice and snowmelt in summer. The amount of snowfall will be large in winter if and only if there is a higher evaporation of water from the oceans in winter. This can happen if and only if the oceans are warm. Hence, an ice age can develop if and only if the oceans are warm in winter!

Wallace Broecker has found another lacuna with the astronomical theory of ice ages. According to this theory, the ice ages should occur alternately in the two hemispheres (see *Figure* 3). The observations indicate however, that the ice ages occur almost simultaneously in both hemispheres. Broecker has argued eloquently that the deep ocean circulation must play an important role in communicating the changes that occur in one hemisphere to the other hemisphere. The differences in salinity and temperature in different parts of the ocean drive the circulation in the deep oceans. This is known as the thermohaline circulation. It transports heat from the tropics to the poles. The thermohaline circulation in the oceans today enables large portions of Europe to be ice-free. If for some reason this thermohaline circulation weakens or reverses then parts of Europe will experience ice age conditions. Hence, we can infer that changes in ocean circulation can trigger ice ages. What factors can change the nature of the thermohaline circulation of the oceans? The salinity of the surface layers of the ocean is determined by the balance between net evaporation (i.e., rainfall – evaporation) and net inflow from rivers or sea ice, or ice sheets. If the ocean surface layer becomes more saline it can become sufficiently dense to sink to the bottom. On the other hand, if the ocean surface layer becomes less saline (because of higher discharge of fresh water from ice sheets) then it can inhibit thermohaline circulation. The complex interaction between atmospheric hydrological processes (i.e., rainfall and river discharge) and the thermohaline circulation of the ocean have not been understood completely so far. Broecker has proposed that the thermohaline circulation of the ocean has two stable states (*Figure* 6a). One of

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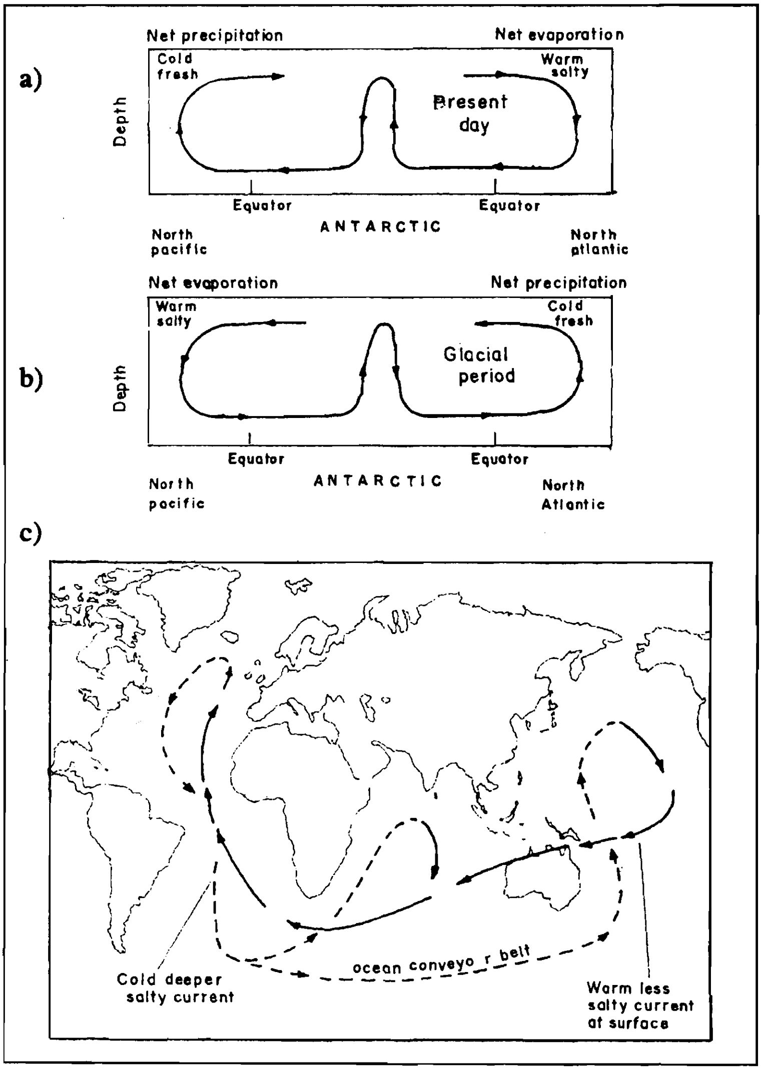

Figure 6. A schematic representation of the two modes of deep ocean circulation. Figures a) and b) show the vertical cross-section of the ocean circulation while Figure c) shows a schematic representation of the global circulation.

these occurs during the inter-glacial period and is similar to what is observed today. A different type of thermohaline circulation occurs during the ice ages (see *Figure* 6b). The switch from one stable state to the other stable state can occur very rapidly. This could be one of the reasons why the ice ages end very rapidly.

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There is one more linkage between the atmosphere and the ocean that is relevant for understanding the periodic fluctuation of climate in the past. The amount of carbon dioxide (CO_2)

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in the atmosphere is governed mainly by the release of CO_2 stored in the deep oceans. The CO_2 content in the surface layers in the ocean is strongly influenced by the amount of biological activity in the surface layers. This depends upon amount of light incident and availability of nutrients and surface temperature. Planktons in the surface of the ocean convert CO_2 to organic carbon, which ultimately sink as debris to the bottom of the ocean. The bacteria in the deep ocean convert the organic carbon to CO_2. The transfer of CO_2 from surface layers to the deep ocean by this process is called 'biological pump'. Oceans hold 60 times as much CO_2 as the atmosphere and hence small changes in the oceanic circulation can cause large changes in atmospheric CO_2. This can influence global climate because CO_2 absorbs strongly the infra-red radiation emitted by the earth's surface but is transparent to solar radiation. Hence, CO_2 is called a greenhouse gas. The amount of CO_2 in the atmosphere has increased dramatically during the last hundred years due to the emission of CO_2 from fossil fuel burning by human beings. There have been large differences in the amount of CO_2 in atmosphere during the ice ages when compared to the period between ice ages (i.e., the inter-glacial period). The measurement of CO_2 in the air trapped in the ice cores in the polar regions shows that the amount of CO_2 during the last ice age (18,000 years ago) was around 200 ppm (parts per million). The amount of CO_2 in the atmosphere today is around 360 ppm (see *Figure* 7). Was a lower amount of CO_2 in the atmosphere in the past partly responsible for triggering the ice age? On the other hand, the lower amount CO_2 in the atmosphere in the past could be due to the changes in ocean circulation during the ice ages. The observations available today cannot resolve whether the changes in ocean circulation triggered an ice age or vice-verse.

Was a lower amount of CO_2 in the atmosphere in the past partly responsible for triggering the ice age?

Concluding Remarks

Today, we know a lot more about the factors that are important for the periodic appearance of ice ages than what scientists knew about fifty years ago. We can assert that the variations in the earth-sun geometry play a central role. There is, however, no

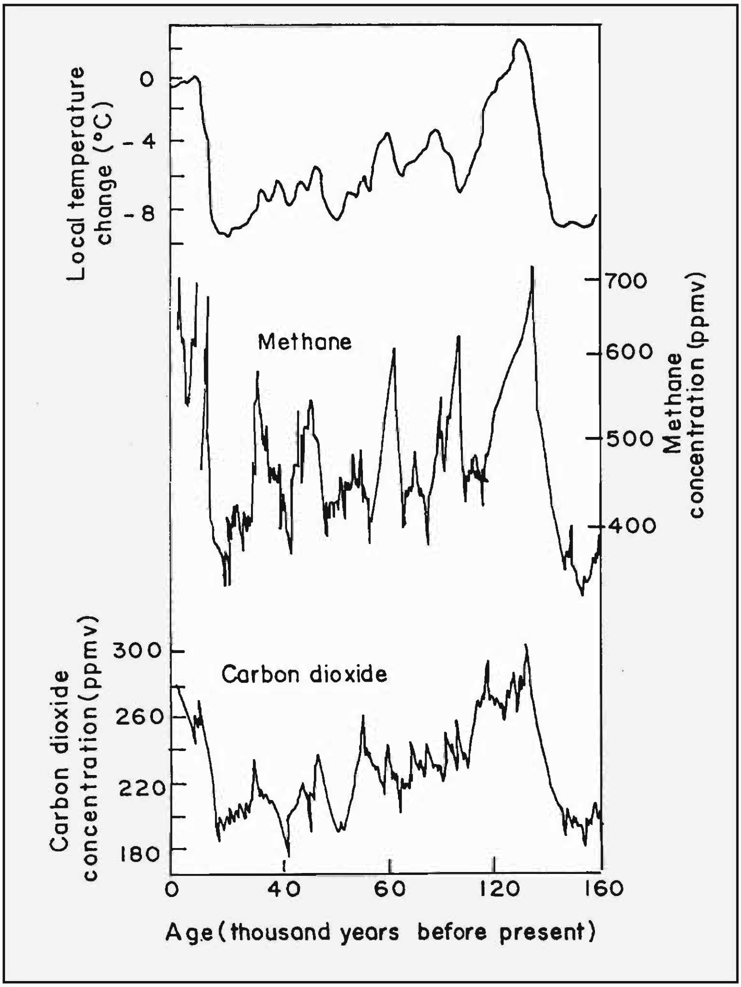

Figure 7. The variations in temperature, methane, and carbon dioxide in Antarctic ice cores.

comprehensive theory that tells us how ice ages begin and why they end so rapidly. We realize that variations in the deep ocean circulation and the CO_2 play an important role in the evolution of ice ages but the precise mechanisms are still unclear. The best summary of our present understanding about ice ages is the statement attributed to Maurice Ewing given below:

"Theories of glaciation have been numerous and characterized by a diversity which indicates that there was not available sufficient information to hold speculation within manageable limits".

Suggested Reading

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[2] A Berger, J Imbrie, J Hays, G Kulka and B Saltzman (Eds.), *Milankovitch and Climate*, D Reidel, Dordrecht, 1984.

[3] G M Goodess, J P Palutikof and T D Davies, *The Nature and Causes of Climate Change*, Belhaven Publishers, 1992.

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[5] W S Broecker, D M Peteet and D Rind, Does the ocean-atmosphere system have more than one stable mode of operation? *Nature*, 315 (1985), 21–25.

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