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The Development of Climate during Earth History
Die Klimaentwicklung im Verlauf der Erdgeschichte

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The Development of Climate during Earth History
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Abstract

During its 4.5 billion year history the Earth has had many climatic states. During the Proterozoic and Phanerozoic It has been an extremely arid planet, an extremely wet planet, an ice-free planet and a planet with extensive ice sheets. Its condition today represents a brief episode of a warm climate within a much longer period of cold glacial climates.

The major factors influencing climate are insolation, albedo, greenhouse gasses, paleogeography, and vegetation. The energy radiated by the sun increases as it grows older. Cyclic changes in the Earth's orbital parameters

affect the amount of radiation received from the sun at different latitudes over the course of the year. During the last climate cycle, the waxing and waning of the northern hemisphere continental ice sheets closely followed the changes in summer insolation at the latitude of the

northern hemisphere polar circle. The intensity of insolation in each hemisphere is governed by the precession and ellipticity of the Earth's orbit. At the polar circle a meridional minimum of summer insolation becomes alternately more and less pronounced as the obliquity of the Earth's axis of rotation changes. Feedback processes amplify the insolation signal.

The naturally occurring greenhouse gasses (H_2O, CO_2, CH_4, O_3) modulate the insolation-driven climate. Without the greenhouse effect the earth's surface would be frozen. In the Precambrian the weaker insolation was balanced by a much higher atmospheric content of greenhouse gasses, mostly the CO_2 that is now trapped in limestone and buried organic carbon. The CO_2 and H_2O combined to weather silicate rocks in such a way as to act as a thermostat to maintain the earth's surface temperature between the freezing and boiling points of water. The reduction of atmospheric CO_2 concentrations during the Cenozoic is frequently cited as the cause of the general cooling of the planet since the middle Eocene.

The changing distribution of land and sea has affected the planet's uptake of energy from the sun and the pattern of its radiation back into space. The changing configurations of the ocean basins have altered the patterns of poleward heat transport.

Plants have changed the planetary albedo and modified the greenhouse by consuming CO_2 and returning soil moisture to the atmosphere. However, during the later Cenozoic many of the freely-transpiring C3 plants have been replaced by water-conserving C4 plants, mostly grasses, that have enhanced the global cooling trend and promoted desertification.

Zusammenfassung

Im Verlauf der letzten 4,5 Milliarden Jahre hat es auf der Erde verschiedene klimatische Stadien gegeben. Während des Proterozoikums und des Phanerozoikums war die Erde sowohl ein äußerst heißer und trockener, als auch ein warmer und niederschlagsreicher sowie ein kalter und eisbedeckter Planet. Der heutige Zustand stellt eine kurze Episode mit warmem Klima in einer wesentlich längeren Phase mit einem kalten glazialen Klima, diese wiederum innerhalb einer längeren Phase mit warmem Klima dar.

Die wichtigsten klimabeeinflußenden Faktoren sind die Sonneneinstrahlung, Albedo, Treibhausgase, die Paläogeographie und die Vegetation. Die von der Sonne ausgestrahlte Energie nimmt mit fortschreitendem Alter zu. Im Verlauf eines Jahres beeinflussen zyklische Veränderungen der orbitalen Erdparameter die Aufnahme der von der Sonne ausgesendeten Strahlung auf verschiedenen Breitengraden. Während des letzten klimatischen Zyklus gab es einen engen Zusammenhang zwischen Ausdehnung und Schrumpfung der kontinentalen

Eismassen in der nördlichen Hemisphäre und den Veränderungen des sommerlichen Sonneneinstrahlungsminimums auf dem Breitengrad des Polarkreises. Die Intensität der Einstrahlung in den beiden Hemisphären wird von der Präzession und dem ellipsenförmigen Verlauf der Erdlaufbahn gesteuert. Am Polarkreis wird die Sonneneinstrahlung mit zunehmender Veränderung der Neigung der Rotationsachse der Erde immer geringer. Rückkopplungseffekte verstärken das Signal der Einstrahlung.
Die natürlich vorkommenden Treibhausgase (H_2O, CO_2, CH_4, O_3) regulieren das von der Sonneneinstrahlung angetriebene Klima. Ohne den Treibhauseffekt wäre die Erdoberfläche gefroren. Im Präkambrium wurde die geringere Sonneneinstrahlung durch einen wesentlich höheren Gehalt der Atmosphäre an Treibhausgasen, vor allem durch den Gehalt an CO_2, welcher heute an Kalksteine und an organischen Kohlenstoff gebunden vorliegt, kompensiert. CO_2 und H_2O zusammen tragen zur Verwitterung von silikatischen Gesteinen bei und agieren dadurch als Thermostat, um die Temperaturen an der Erdoberfläche zwischen dem Gefrierpunkt und dem Siedepunkt von Wasser zu halten. Eine Reduzierung von atmosphärischen CO_2 -Konzentrationen während des Känozoikums wird häufig als der Hauptgrund für ein Abkühlen der Erde seit dem mittleren Eozän angeführt.

Zudem haben auch die veränderte Verteilung der Landmassen und der Ozeane die Aufnahme und Rückstrahlung von Energie auf der Erde beeinflußt. Wechselnde Strukturen der ozeanischen Becken haben die Muster eines polwärts gerichteten Wärmetransports ebenfalls immer wieder verändert.

Pflanzen haben die planetare Albedo geändert. Durch ihre CO_2 -Aufnahme und Rückgabe von Bodenfeuchte in die Atmosphäre haben sie auch zu veränderten Treibhausbedingungen beigetragen. Während des späten Känozoikums wurden jedoch viele C3-Pflanzen von wasserspeichernden C4-Pflanzen verdrängt. Vor allem Gräser haben den globalen Abkühlungstrend verstärkt und zur Ausbreitung von Wüsten beigetragen.

Introduction

During its 4.5 billion year history the Earth has had many climatic states. During the Proterozoic and Phanerozoic its climate has varied from hot and arid to warm and wet to cold and ice-covered. Its modern condition represents a brief episode of warm climate within a longer period of cold glacial climates that have replaced much longer-lasting conditions of global warmth. The climatic history of the Earth over the last 600 million years is summarized in Fig. 1.
Conditions like those at present have been characteristic of interglacial episodes, but these are short and have persisted for less than 10% of the past million years. Large ice sheets have been the most prominent features of northern hemisphere geography during most of the late Quaternary. They have acted as high frigid plateaus blocking the zonal atmospheric circulation and creating their own atmospheric pressure systems. Centered on 60-65 ° N, they have forced a sharp temperature gradient to the equator. Sea level has been lower throughout most of the Quaternary, with shelf seas having a much smaller areal extent than at present. The cooler global temperatures during the glacial episodes imply a lesser role for latent heat transport by the atmosphere, and hence a different partitioning of energy transport between the ocean and atmosphere.
However, continental ice sheets are also not typical of the planet's "average" state. Such ice sheets have been present during no more than 30% of the Phanerozoic (CROWELL, 1982). The planet's "normal" state is to have an equator-to-pole temperature gradient less than half that of today, and to be free of large continental ice sheets (FRAKES et al., 1992). FISCHER and ARTHUR (1977) coined the terms "icehouse" and "greenhouse" for these contrasting states of the Earth's climate. FRAKES et al. (1992) discussion of the Phanerozoic history of the Earth in terms of an alternation between these two states forms the basis for Fig. 1.

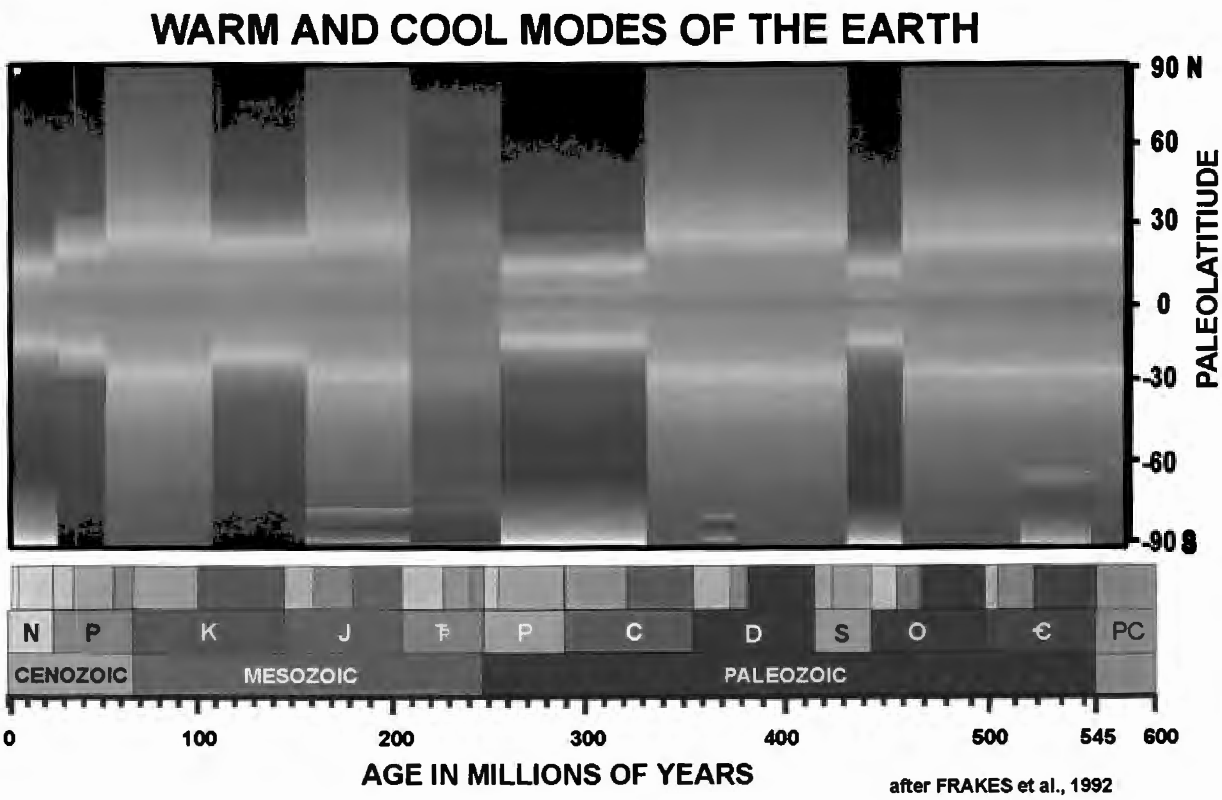

Fig. 1: ***Warm and cool modes of the Earth through the Phanerozoic. Temperatures are indicated semi-quantitatively, with red being very hot, orange being hot, yellow being warm, green being moderate, blue being cold, and which indicating ice-covered. The temperature history is based on the discussions in FRAKES et al. (1992) and other sources.***

Even more extreme climatic conditions may have existed during the Precambrian. There is growing evidence that the Earth may have been completely covered by snow and ice at several times during the Proterozoic (HOFFMANN et al., 1998). These "Snowball Earth" glaciations ended with brief episodes of an intense greenhouse condition. It has been suggested that these extreme climatic alternations may have set the stage for the development of Metazoa and were a necessary precursor to the Cambrian explosion of life.

The major factors influencing the climate are insolation, greenhouse gasses, paleogeography, and vegetation, as shown in Fig. 2. The following sections treat each of these topics although the climate as a whole is the result of their complex interplay.

Insolation and Albedo

Insolation and albedo determine how much energy planet Earth receives from the sun. Insolation is the amount of radiation from the sun received at the top of the atmosphere; the albedo is the proportion of the insolation that is reflected back into space.

Studies of solar evolution indicate that energy radiated by the sun increases as it grows older (NEWMAN and ROOD, 1977; ENDAL, 1981; GILLILAND, 1989). At the time of the accretion of the Earth, the radiation from the sun is estimated to have been 25 - 30 % less than it is today. The problem of the "faint young sun" was a major topic that provided the first wedding of paleoclimatology and climate modeling (WETHERALD and MANABE, 1975; SELLERS, 1990). In the 1970's it was thought that although there was evidence for water on the surface of the planet since early in the Precambrian, there was no evidence that

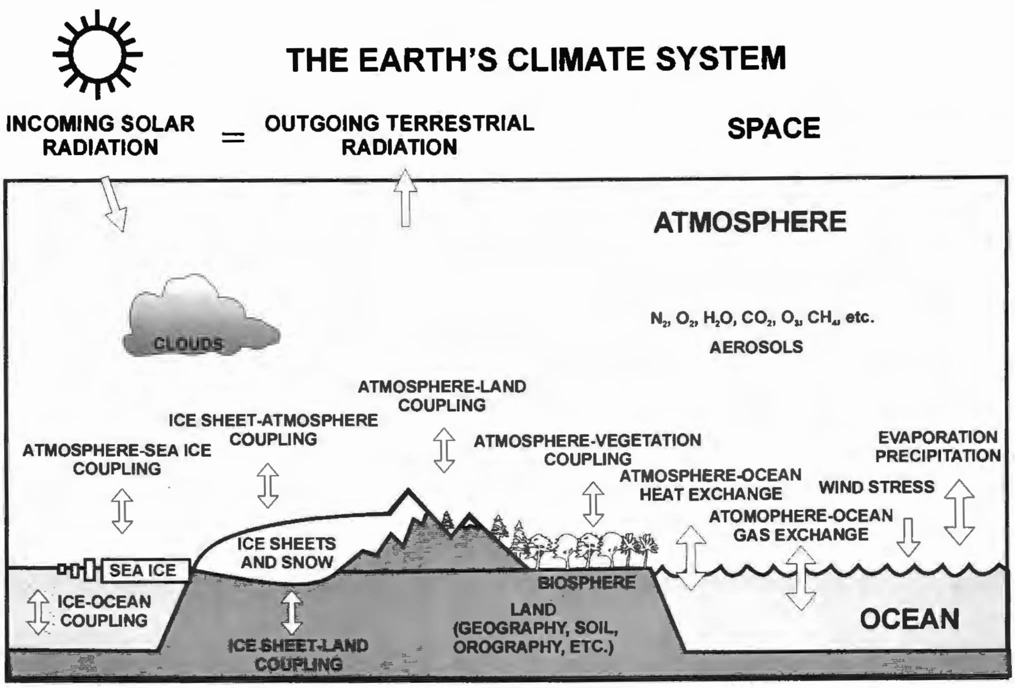

Fig. 2: The Earth's climate system, showing the major interactions between components of the system.

the planet had ever been completely frozen. Yet the lower level of radiation of the early sun implied that unless there was some offsetting factor, such as a higher greenhouse gas content in the atmosphere, the Earth should have been completely frozen (OWEN et al., 1979). At that time it was argued that if the Earth were ever to freeze completely over, the high albedo of ist surface would make it impossible for it ever to thaw. The "faint young sun paradox" was explored using a simple energy balance argument: radiation received from the sun must equal radiation into space from the Earth (NORTH et al., 1981).

Figure 3 shows how incoming solar radiation is reflected, absorbed, and returned to space. It is evident that the Earth's albedo (0.30) is mostly a function of cloud cover and backscattering from the air. Only about 4 % of the incoming radiation is reflected from the surface. The albedo of the Earth is unique among the planets of the solar system. The rocky planets which essentially lack an atmosphere (Mercury and Mars) are much less reflective, having much lower albedos of 0.06 and 0.16 respectively. The planets with a thicker cloud-filled atmosphere (Venus, Jupiter, Saturn, Uranus, Neptune) are much more reflective, having albedos of 0.70 or higher. Changes in the cloud cover of the Earth could result in significant differences in its albedo, but virtually nothing is known about the long-term history of clouds and atmospheric backscattering.

The simplest energy balance models, used to estimate the planetary temperature under different conditions, treat the entire Earth as a single point. They were use in early investigations of the "faint young sun" problem. Following the Stefan-Boltzman law for black-body radiation, the energy balance for the Earth can be written as:

$$Q_o (1 - \alpha_p) \pi r^2 = 4 \pi r^2 \sigma T^4$$

The left-hand side of the equation is the absorbed short -wave solar radiation: Q_o is the solar constant (presently1360 W m^{-2}), α_p is the present planetary albedo (0.30), and r is the radius of the Earth (6.371 x 106 m). πr^2 is the area of a disc the size of the earth intercepting sun's radiation. The right-hand side of the equation is the radiation emitted by the Earth, where $4 \pi r^2$ is the area of the surface of the earth, σ is the Stefan-Boltzmann Constant (5.67 x 10^{-8} W $m^{-2} K^{-4}$), and σT^4 is the outgoing radiation per unit area (Stefan's Law). The area of a disc the size of the

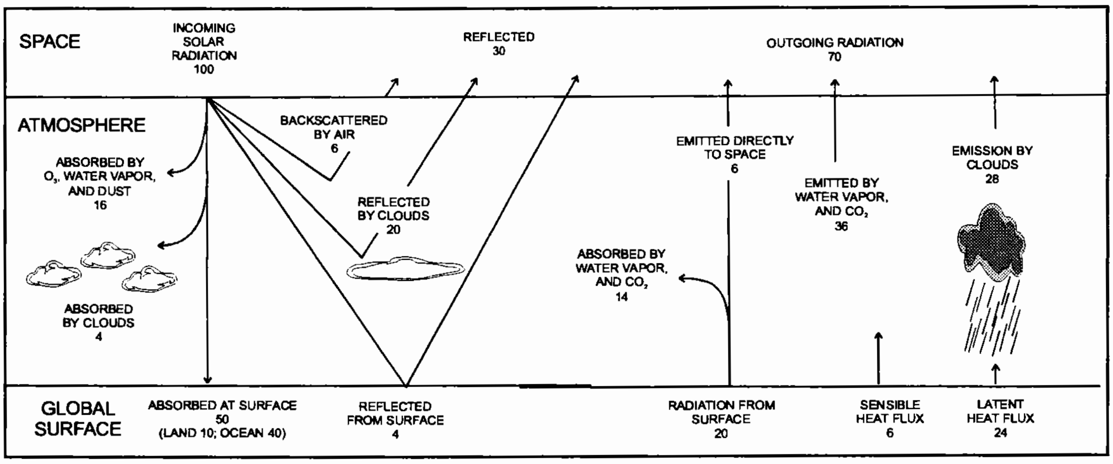

Fig. 3: The Earth's global energy budget, showing the amount of energy reflected, absorbed and re radiated by components of the Earth system. Numbers represent the percentage of incoming solar radiation.

Earth, and of its spherical surface differ by a factor of 4, so that the average energy received by the planet is 1360 / 4 = 340 W m^{-2}. The effect of changing solar the solar constant and /or the Earth's albedo is shown in Fig. 4.

This simple calculation of the temperature of the Earth's surface required to re radiate energy in balance with the absorbed solar insolation (340 W m^{-2} x (1 - 0.30) = 238 W m^{-2}) using the Stefan-Boltzmann Law indicates that the present-day surface temperature should be 254.5 K or -18.5°C (PEIXOTO and OORT, 1992). However, the mean surface temperature of the earth today is about 15°C; the 33.5°C difference between the 18.5°C calculated and the +15°C observed is due to the effect of atmospheric greenhouse gases. With incoming radiation 20% less than it is at present but liquid water present on the planet's surface, there must have been a much more effective greenhouse than that we have today. The change in luminosity of the sun is though to be linear during this phase of its development, so the increase in the solar constant since the beginning of the Phanerozoic is only about 3%.

In contrast to the slow steady increase of the sun's luminosity, cyclic changes in the Earth's orbital parameters affect the amount of radiation received from the sun at different latitudes over the course of the year. During the last climate cycle, the waxing and waning of the northern hemisphere continental ice sheets closely followed the changes in summer insolation at the latitude of the northern hemisphere polar circle. The intensity of insolation in each hemisphere is governed by the precession and ellipticity of the Earth's orbit. At the polar circle a meridional minimum of summer insolation becomes alternately more and less pronounced as the obliquity of the Earth's axis of rotation changes. Feedback processes amplify the insolation signal.

The annual variation in insolation at different latitudes which result from the tilt of the Earth's axis relative to the plane of the Earth's orbit around the sun produces the four seasons: spring, summer, fall, and winter. The intensity of the seasonal insolation varies on time scales of 104-105 years because of variations in the Earth's orbital parameters induced by the combined gravitational attraction of the moon, sun and other planets (BERGER, 1981). The major orbital variations affecting insolation are shown in Fig. 5. The ellipticity of the Earth's orbit changes the Earth-Sun distance during the course of the year; it varies on a roughly 95,000 year time scale, with a longer cycle of variation of about 400,000 years (Fig. 5a). The precession of the long axis of the elliptical orbit changes the time of the year when the planet is closest tothe sun and has a period of about 105,000 years

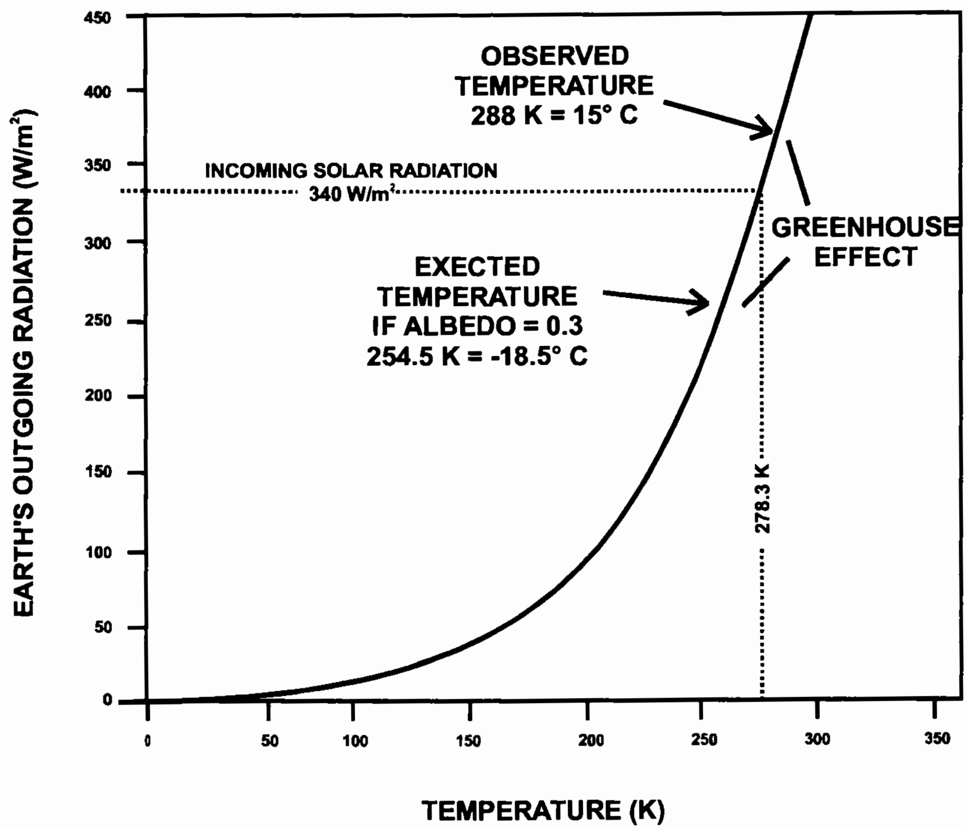

Fig. 4: Balance between incoming and outgoing radiation, and the greenhouse effect. For discussion see text.

(Fig. 5b). The precession of the Earth's axis of rotation also affects the season at which the earth is closest to the sun and has a period of 27,000 years (Fig. 5c). The combined effect of precession of the axis of rotation and the elliptical orbit is to produce an apparent period of 23,000 years. Similarly, the cyclic changes in ellipticity combines with these motions to produce another apparent period of 19,000 years. These three orbital variations combine in such a way that perihelion coincides with seasonal summer in each hemisphere about every 21,700 years. This effect is termed the precession of the equinoxes, and is shown in Fig. 5d. Although these orbital variations have a negligible effect on the total amount of insolation received by the Earth during a year, they result in major redistributions of the energy received at different latitudes during different seasons. The distribution of the energy received at perihelion and aphelion is modulated by the precession of the elliptical orbit and axis of rotation, so that the effects are concentrated alternately in the northern and southern hemispheres. As a result there is an oscillation of the intensity of seasonality between the northern and southern hemispheres, a displacement of the caloric equator into the hemisphere closest to the sun during its seasonal summer, and shifts of the low latitude climate zones. At present the Earth is at perihelion shortly after the northern hemisphere winter solstice, so the seasonal contrast is minimal in the northern hemisphere and maximal in the southern hemisphere. These effects are shown in Fig. 6 which presents the summer-winter and equinoctial insolation patterns for present.

Another orbital variation is the obliquity ("tilt") of the Earth's axis of rotation relative to the ecliptic (plane of the orbit), which varies between 22°2' and 24°30' on a 41,000 year time scale (Fig. 5e). The obliquity of the axis of rotation determines the position of the tropics and the polar circles. The tilt of the axis produces a local insolation minimum during

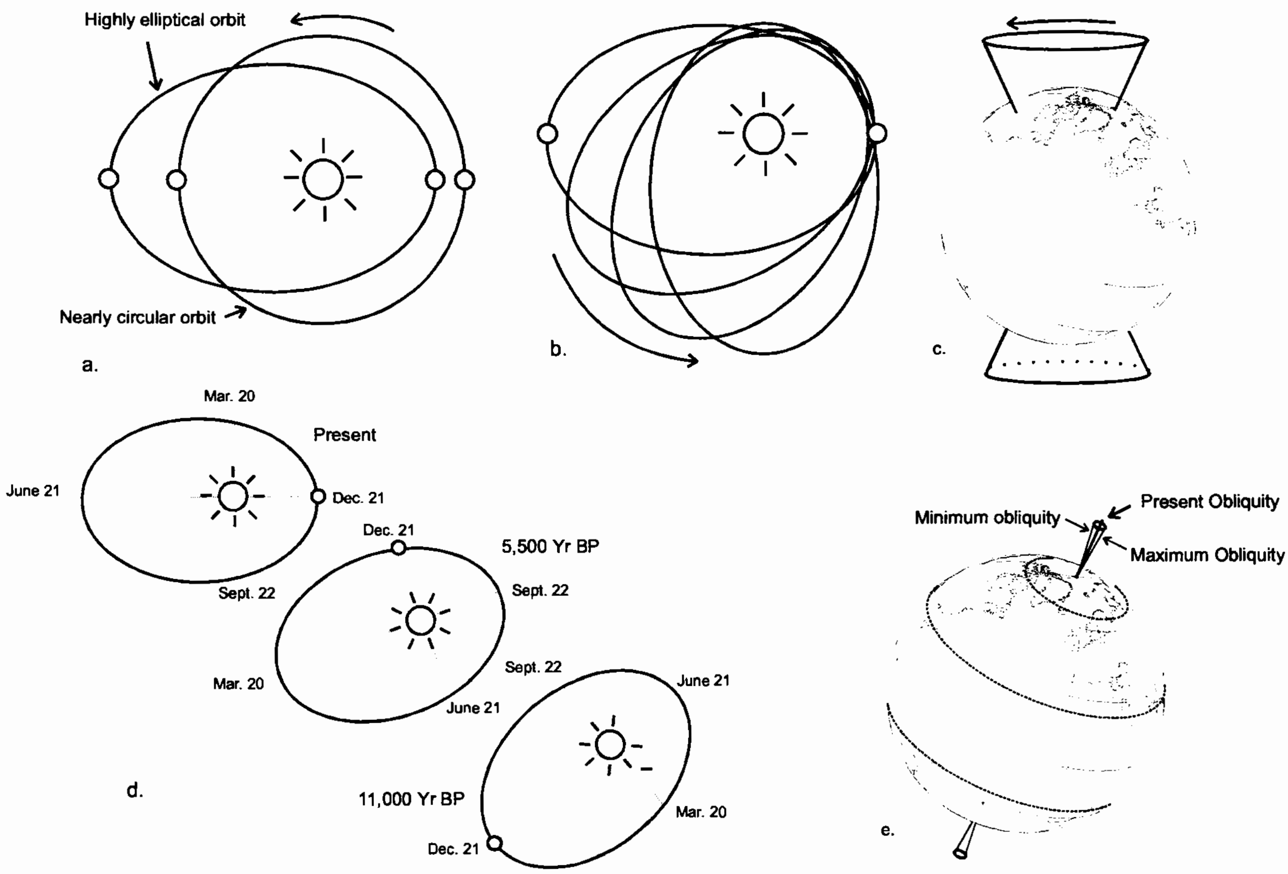

Fig. 5: Variations in the Earth's orbital and rotational parameters. For discussion see text.

the summer in each hemisphere, as shown in Fig.6. Changes in obliquity redistribute the energy received at high and low latitudes, alternately concentrating and dispersing the insolation poleward of the polar circle. This results in alternate intensification and diminishing of the meridional minimum of summer insolation associated with the polar circle, shown in Fig. 6.

The effect is identical in both northern and southern hemispheres. MULLER and MACDONALD (1995) have suggested that another orbital variation may be responsible for the 100-kyr cycle of glaciations and interglacials: the inclination of the Earth's orbit relative to the Zodiac, the average plane of planetary orbits in the solar system. They found that the inclination minima have the same period as glacial maxima, but precede them by 33 3 kyr. There is a concentration of dust in zodiacal plane ("zodiacal cloud"), and as the inclination of the Earth's orbit passes through it the insolation received by the Earth must be reduced. They suggested that if this is the cause of the 100-kyr glacial cycles, it should be possible to find a 100-kyr cycle in the rate of accumulation of meteoritic dust. Such a periodicity in the accretion of interplanetary dust has subsequently been reported by KORTENKAMP and DERMOTT (1998).

Largely because of the increase in day length during the summer, the polar regions receive more insolation than other parts of the Earth during this season. During the summer there is a secondary insolation maximum at about 40° as a result of both the increase in day length and elevation of the sun. Fig. 6 shows the minimum in summer insolation at the latitude of the polar circle, about 66.5°N and S. This summer insolation minimum is closely associated with the growth and decay of the northern hemisphere ice sheets. Snow which accumulates during the fall winter and spring is most likely to remain where the solar insolation is minimal during summer,

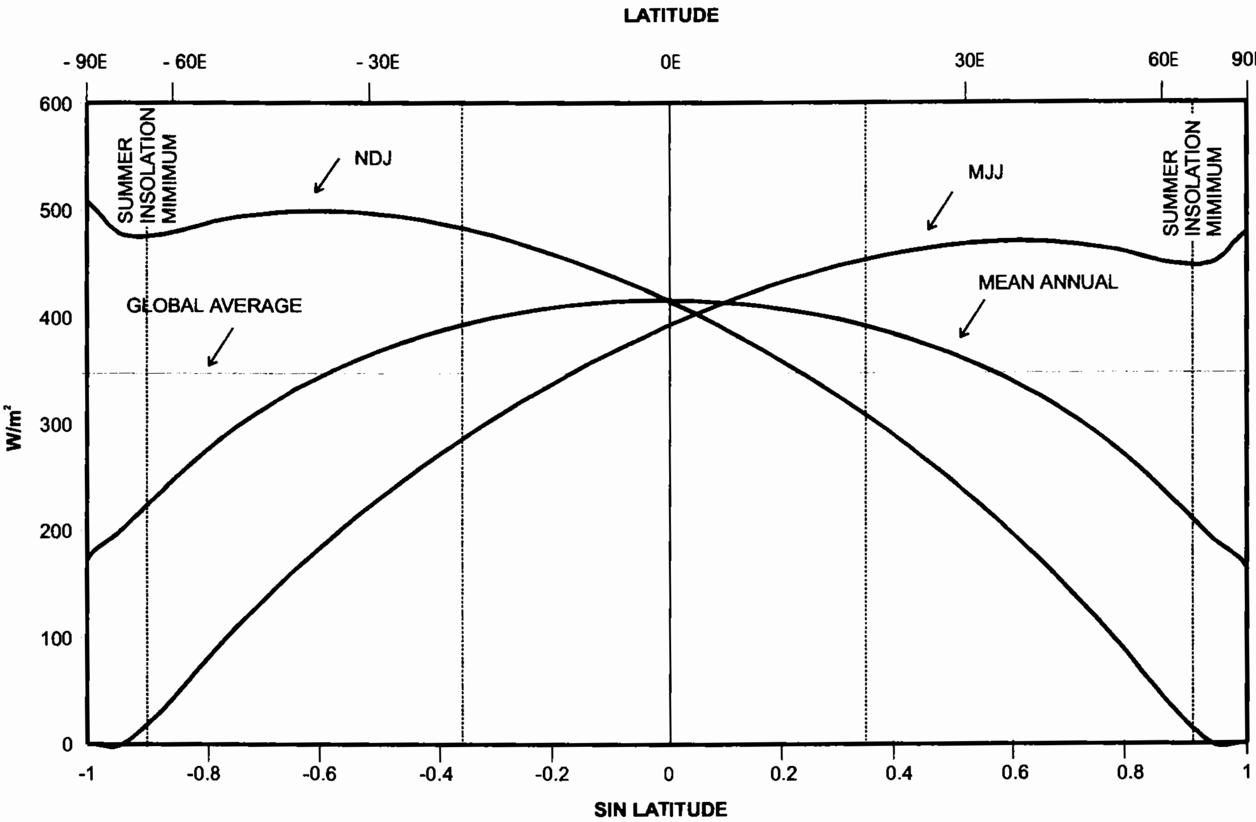

Fig. 6: Variations in insolation at the top of the atmosphere during summer, winter and equinoctial seasons. Note the summer insolation minima near the polar circles, discussed in text. The x-axis is a linear representation of the sine of the latitude, correctly showing the relative areas in each latitude band.

and uplands near the polar circle appear to have served as the site of nucleation of the Greenland, Laurentide, and Scandinavian ice sheets

Climate models suggest that the changes in solar insolation resulting from the orbital variations are too small to initiate the glacial-interglacial cycles. There are of two sorts of feedback mechanisms that might amplify the signal, those directly affecting the planetary radiation balance, and those changing the concentrations of greenhouse gasses in the atmosphere. Mechanisms affecting the radiation balance include the ice-albedo feedback, isostatic adjustment of the earth's surface to the ice load, instability of ice sheets grounded below sea level, effect of meltwater on supply of moisture to the ice sheets, changes in the atmospheric dust flux, and changes in vegetation (BROECKER and DENTON, 1989; BROECKER, 1995). The feedback mechanisms changing greenhouse gas concentrations and their climatic effects are discussed in the next section.

The ice-albedo feedback is most directly related to insolation. The high reflectivity of snow in upland areas reduces the absorbed insolation. This helps to protect the snow and ice from summer melting and results in a strong positive feedback promoting further accumulation of snow (FLINT, 1943; BUDYKO, 1968; SELLERS, 1969; IVES et al., 1975; CROWLEY and NORTH, 1991).

Isostatic adjustment of the Earth's surface to the ice loads has been proposed as the cause of the 100,000 year periodicity of growth and decay of the Quaternary northern hemisphere ice sheets (WEERTMAN, 1976; POLLARD, 1982; HYDE and PELTIER, 1985). As the ice sheet grows, it depresses the land surface by about 1/3 of its own thickness. If the equilibrium snow line, which separates the region of accumulation from that of ablation, were to remain constant for a long period of time, the ice sheet would reach a steady state. However, the equilibrium snow line moves up and down in response to insolation changes faster than isostatic adjustment can take place. When the equilibrium snow line rises, the area of the ice sheet undergoing melting increases and the area of ice accumulation decreases. Because of the long response time of the isostatic adjustment to the lighter load, the area of ablation and melting continues to increase; this positive feedback mechanism may explain the rapid melting of the northern hemisphere ice sheets at the end of each glacial.

The inherent instability of ice sheets grounded below the level of surrounding fresh or marine waters has been cited as a cause of rapid deglaciation (ANDREWS, 1973). Rising sea level buoys grounded maritime ice sheets, making them ripe for surging. The layers of ice-rafted detritus deposited by flotillas of icebergs, known as Heinrich Events (HEINRICH, 1988; BROECKER et al., 1990; ANDREWS and TEDESCO, 1992; MACAYEAL, 1993; BOND and LOTTI, 1995), reflect surging of maritime ice sheets.

During the Quaternary, changes in vegetation have affected both the planetary albedo and the concentration of greenhouse gasses in the atmosphere. During interglacial episodes the high albedo (60-95%) ice and snow cover of northern North America, Europe, and Asia was replaced by low albedo (15-20%) evergreen forests and tundra (COHMAP, 1988; OVERPECK et al., 1992), and the extensive sand deserts that existed during glacial times at lower latitudes were replaced by tropical forests and grasslands (Sarnthein, 1978).

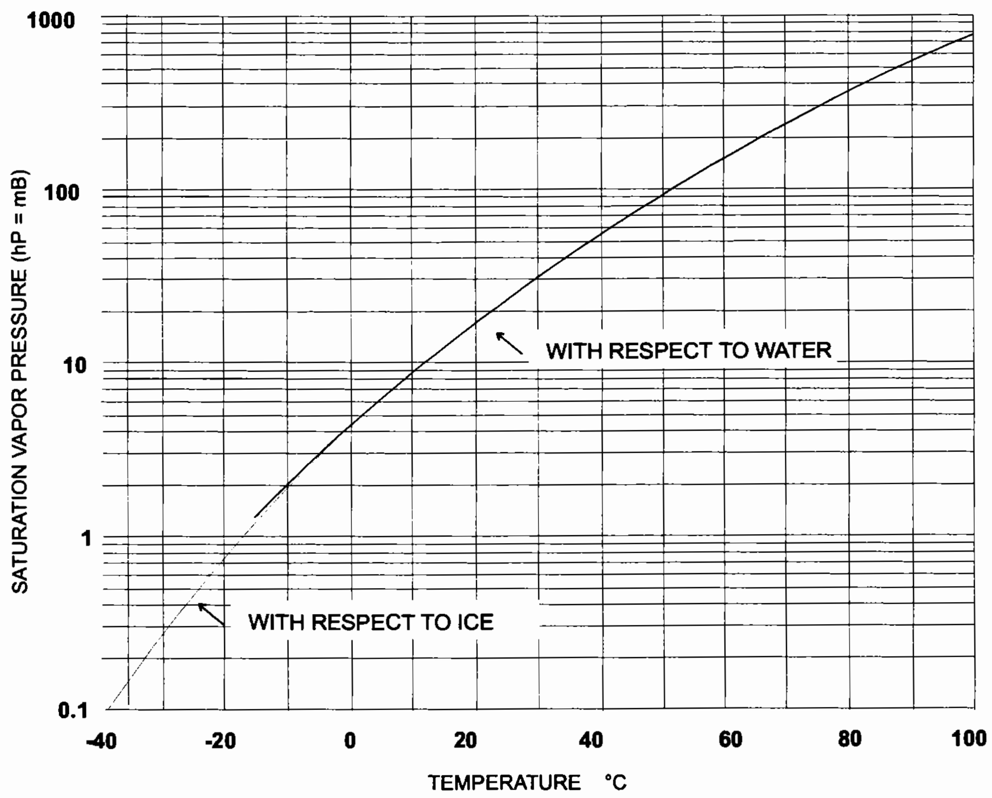

Fig. 7: Saturation vapor pressure of water at different temperatures. The amount of water that can be evaporated approximately doubles with every 10°C increase in temperature.

Greenhouse gasses

Atmospheric greenhouse gasses are another major factor in the climate system. All tri atomic and more complex air molecules (H_2O, CH_4, CO_2,O_3, man-made chlorofluorocarbons, etc.) capture and re radiate incoming and/or outgoing radiation (WELLS, 1986), as shown in Fig. 3.

Water vapor is the most abundant and effective greenhouse gas, but its content in the atmosphere is strongly dependent on temperature, as shown in Fig. 7. Because of today's sharp meridional temperature gradient, the effectiveness of water vapor as a greenhouse gas is limited to the equatorial and tropical regions. Because water vapor condenses with cooling of rising air, most of the moisture in the equatorial and tropical atmosphere is concentrated in the lower troposphere. Other greenhouse gasses are not temperature dependant, and their effects are particularly prominent in the polar regions, where the water vapor content is low.

Methane is also very effective as a greenhouse gas, but it is relatively short-lived, rapidly becoming oxidized in the atmosphere. Nevertheless, it has been suspected to have played a significant role in the climate of the past. Some rapid global warming events, such as the Late Paleocene Thermal Maximum (KENNETT and STOTT, 1991; ZACHOS et al., 1994), are thought to be the result of massive release of methane as a result of decomposition of gas clathrates on the upper continental slopes (DICKENS et al., 1995, 1997). In addition to its formation from the anaerobic decomposition of organic matter in lacustrine and marine sediments, methane is produced in swamps, bogs, and by ruminant animals, such as cows and perhaps dinosaurs (BAKKER, 1986). Ice core studies have shown that during the Last Glacial Maximum methane levels in the atmosphere were about half of their pre-industrial value (STAUFFER et al., 1988). It is thought that the increase in methane since the last glaciation is most likely due to the increase in area of high-latitude peat bogs and lower latitude coastal swamps, but release from clathrates cannot be excluded. The sudden episodes of warming that have punctuated the history of the Quaternary (Dansgaard-Oeschger Events) are thought to be the result of catastrophic releases of methane from marine sediments (KENNETT et al., 2000).

Carbon dioxide, CO_2, is the greenhouse gas suspected of having had the greatest role in influencing the Earth's climate since the Archaean. BUDYKO and RONOV (1979), on the basis of the masses of carbonate rocks of different ages preserved on the continents, proposed that increased levels of atmospheric CO_2 were responsible for the warm polar conditions that prevailed during the Late Cretaceous. They also reasoned that the CO_2 content of the atmosphere should parallel volcanic activity, but CO_2 is also introduced by weathering of sedimentary rocks containing organic carbon. The amount of CO_2 in the atmosphere reflects the balance of the supply from volcanoes and weathering of organic carbon in sediments, and the weathering of silicates through the carbonation reaction and burial of organic carbon in young sediments (BERNER, 1999). Changing atmospheric CO_2 concentrations has been accepted as the thermostat mechanism responsible for maintaining the Earth's surface temperature within the range of liquid water (WALKER et al., 1981; KASTING 1989). As temperatures increase, the rate of silicate weathering would increase, doubling with every 10°C rise. As temperatures decline, the rate of silicate weathering through the carbonation would also decrease to cease completely when water freezes (BERNER and BERNER, 1997). It is interesting that the amount of C present as CO_2 in the atmosphere of Venus is almost the same as the amount of C in carbonate rocks and buried organic matter on Earth.

Changes in atmospheric CO_2 are thought to be responsible for long-term climatic trends, such as the global cooling since the Eocene (RAYMO et al, 1988; RAYMO, 1991). Shorter-term variations of atmospheric CO_2 are known to occur during the Quaternary, on both glacial-interglacial and shorter time scales. Ice cores indicate that the variations in temperature are closely paralleled by variations in atmospheric CO_2 from pre-industrial levels of about 280 ppm to about 195 ppm during the Last Glacial

Maximum. It is thought that these changes may reflect the vigor of the global thermohaline circulation system ("The Great Conveyor," BROECKER, 1987, 1991). If the thermohaline circulation system runs rapidly, the deep ocean is well ventilated, but if it is sluggish, CO_2 accumulates in the deep sea, lowering its concentration in the atmosphere.

Climate model simulations with atmospheric CO_2 concentrations higher than present clearly show that the increased CO_2 raises the temperature of the polar regions while having little effect on the tropics and equatorial region (SCHLESINGER, 1989). This is because the warm lower atmosphere of low latitude areas already has a high content of the more effective greenhouse gas, water vapor. Adding CO_2 to the atmosphere most strongly affects the colder high latitude areas where the water vapor content of the air is low. The overall effect is to produce strong polar warming. The warmer polar air can then hold more water vapor, creating a positive feedback enhancing the greenhouse effect. It is generally accepted that the warm polar regions characteristic of most of the Phanerozoic were the result of atmospheric CO_2 concentrations at least several times that of today.

The 30% glacial-interglacial variations in CO_2 content of the atmosphere are minor compared with those between the warm "greenhouse" Earth and its present "icehouse" state, thought to be in the order of 400-700%. BERNER (1994), on the basis of a geochemical model, estimated levels of atmospheric CO_2 in the Early Paleozoic to be 16 - 20 times present. The geochemical model is in general agreement with evidence from paleosols (CERLING, 1991). Atmospheric CO_2 levels in the Precambrian may have been even higher, compensating for the weaker solar radiation.

The Snowball Earth hypothesis (HOFFMAN et al., 1998) postulates that it was a fall in atmospheric CO_2, perhaps as the result of an episode of unusually high productivity and burial of organic carbon in the ocean, that initiated glacial conditions. The ice-albedo feedback then led to a runaway icehouse, producing ice sheets on land and completely freezing over the ocean. Continued production of CO_2 from volcanoes then raised its concentration in the atmosphere to 400 times present levels. Such a high concentration would warm global temperatures to the point that the ice cover would melt, but then an extreme greenhouse condition would exist for a brief period until carbonate sedimentation in the ocean reduced the atmospheric CO_2 to lower levels.

Paleogeography

Distribution of land and sea

LYELL (1830) proposed that a different latitudinal distribution of land and sea was the cause of the differences in climate recorded by the geologic record. More extensive land areas in the polar regions would result in a cooler, but more land in the equatorial regions a warmer, Earth. Lyell was convinced that the latitudinal distribution of land and sea had been different in the past, and was responsible for the deposition of the Carboniferous coals and for the differences in the molluscan assemblages of Mesozoic and Cenozoic deposits.

KRIECHGAUER (1902) had suggested polar wander as a cause for the different latitudinal distribution of landmasses in the past, but it was WEGENER (1912, 1929) who formally proposed that the horizontal movement of the major continental blocks ("continental drift") had produced the climatic changes observed in the geologic record. Wegener's hypothesis was that the continental blocks had moved beneath climatic zones that were fixed with respect to latitude. We now know that during the Mesozoic and Cenozoic, most of the motions of continents are zonal, parallel to latitude. Only India and Australia have had a large meridional component in their motion.

Sea level also makes major changes in paleogeography. Today only a narrow shelf area along the margins of the continents is flooded, and the continents were almost totally emergent during the low sea-level stand of the last glaciation. At other times during the Phanerozoic, as 30 % or more of the continental block area has been flooded, and contiguous land areas were greatly reduced.

Using global paleogeographic maps based on plate tectonics, BARRON et al. (1980) speculated that changes in land-sea distribution since the Jurassic altered the surface albedo enough to be the underlying cause of climate change. Following CROWELL and FRAKES (1971), BARRON (1981) concluded that the presence or absence of land at the pole was one of the most critical factors affecting the global climate.

To explore the effects of changing paleogeography, BARRON and WASHINGTON (1984) conducted a series of insightful experiments with the NCAR (U.S. National Center for Atmospheric Research) Atmospheric General Circulation Model (AGCM) CCM1. A complete account of these experiments has been discussed in the light of subsequent studies by BARRON and MOORE (1994). Five sensitivity experiments were performed, all using modern mean annual solar insolation. The experiments compared the results of simulations for the present with the Cretaceous paleogeography of BARRON et al. (1981), but East and West Antarctica blocks translated to conform to TARLING (1978), and using the paleotopography shown in the Cenomanian maps of PARRISH and CURTIS (1982, figs. 3, 4). For each of the five sensitivity experiments only one paleogeographic variable was changed. The first experiment used present-day geography and explored the effect of changing the albedo of the surfaces of Antarctica and Greenland from snow-covered to snow free, eliminating the present ice-albedo feedback. The result was an increase of the global mean temperature of 0°C and an increase of Antarctic temperatures of 10-15°C. The second experiment removed the relief from the present-day continents to explore the effect of topography on the climate. The global mean temperature increased 1.1°C, but the temperature of present lowland areas decreased 1-7°C while the temperature of the Antarctic increased by 15°C. The third experiment moved the flat continents with present-day shorelines to their Cretaceous positions. This produced an increase of 3.1°C in global mean temperature, with temperatures in the northern polar region increasing by 21°C. The fourth experiment changed the shorelines to reflect the higher sea-level of the mid-Cretaceous. Although it had been anticipated that the much greater area of low-albedo epicontinental seas would result in significant warming, the global mean temperature decreased by 0.1°C, largely as a result of cloud production over the shallow seas. The fifth experiment added Cretaceous topography, this resulted in a decrease of the global mean temperature of 1.1°C, exactly compensating for the temperature decrease that had resulted from removing topography from the present land areas carried out in the second experiment. Comparing the end result of these simulations using mid-Cretaceous geography directly to a simulation for the present, BARRON and MOORE (1994) found a global average temperature increase of 4.8 K for the mid-Cretaceous, with tropical temperatures increasing 2°C, the North Pole 15°C and the South Pole 39°C warmer than in the present-day simulation. BARRON and WASHINGTON (1985) concluded that the major factor causing the globally warm climate of the Cretaceous was not paleogeographic, but a higher concentration of atmospheric CO_2.

Opening and Closing Oceanic Gateways

It has long been suspected that the opening and closing of gateways between ocean basins must play a major role in climate change (BERGGREN and HOLLISTER, 1974; BERGER et al., 1981; HAQ, 1984) but descriptions of the effects have remained mostly qualitative and speculative. Interocean gateways that have played an important role in the development of the climate during the Cenozoic are shown in Fig. 8. The closure of the Tethyan passages that promoted zonal low-latitude circulation in the Mesozoic and early Cenozoic, and opening of high-latitude passages around Antarctica has had a profound effect on the global ocean circulation and its ability to transport heat from the equatorial region to higher latitudes. The onset of glaciation of Antarctica was linked to the opening of the passage between the Australian Block (including Tasmania) and East Antarctica (KENNETT, 1977), and expansion of Antarctic Glaciation to the opening of the Drake Passage (WISE et al., 1985). Paleoceanographers have assumed that the opening of the Tasman-

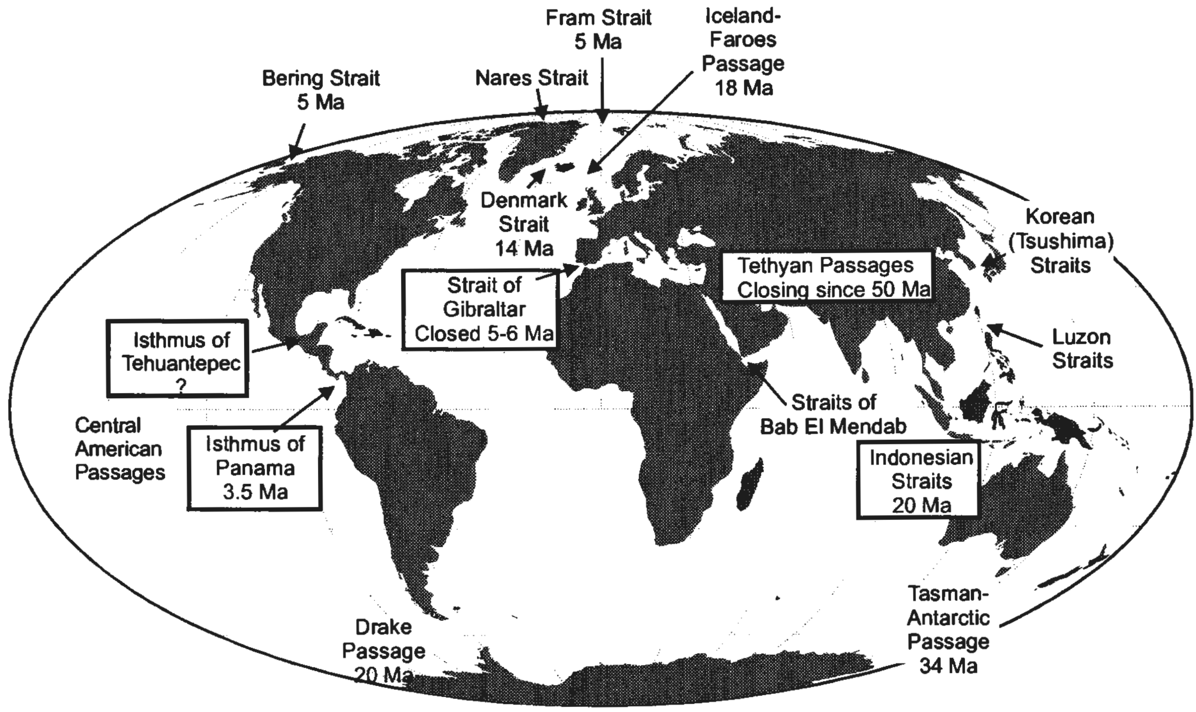

Fig. 8: Major interocean gateways active during the Cenozoic. Square frame indicates that the gateway has been closing, no frame indicates that it has been opening. Ages indicated are approximate time of complete closure or opening.

Antarctic Passage (Fig. 8) and the Drake Passage (Fig. 8) led to isolation of the Antarctic continent, and resulted in a sharp meridional thermal gradient that allowed glaciation of the Antarctic continent. HAUG and TIEDEMANN (1998) have shown that the closure of the low latitude connection of the Atlantic and Pacific across Panama is the critical event in inducing the northern hemisphere glaciation.

Globally, the ocean and atmosphere are thought to carry roughly equal amounts of energy poleward, but their relative importance varies with latitude. The ocean dominates the system by a factor of two at low latitudes, and the atmosphere dominates by a similar amount at high latitudes. ROOTH (1982) noted that the Subtropical Convergences at about 45° N and S act as barriers to poleward heat transport by the ocean. Only where deep water forms at high latitudes are warm subtropical waters drawn poleward to higher latitudes to replace the sinking waters. At present about 80% of the ocean heat transport is carried by surface currents and 20% by the thermohaline circulation.

Interocean gateways can promote or restrict meridional flow of surface and deep waters. However, the effect of a gateway depends on its width, depth and location. At present the ocean between the Subtropical Fronts that lie at about 45° N and S is stratified, whereas poleward of the polar fronts at about 55° N and S the water convects to the ocean floor, as shown in Fig. 9. Along and between the Subtropical and Polar Fronts waters sink, forming the thermocline and intermediate water masses that underlie the tropical-subtropical gyres. Intermediate waters can also have their origin in the outflow of negative water-balance (evaporation > precipitation + runoff) marginal seas. In the tropics and subtropics, the surface currents of the anticyclonic gyres are a few tens of meters thick along the eastern margins of the oceans and several hundreds of meters thick along the western margins, so that these currents can be intercepted by relatively shallow gateways. The Kuroshio Current, for example, passes through the Tsushima Straits But is then partially trapped in the Sea of Japan, reducing its capability to transport heat northward. Between the Subtropical Fronts the depths from the base of the surface currents to

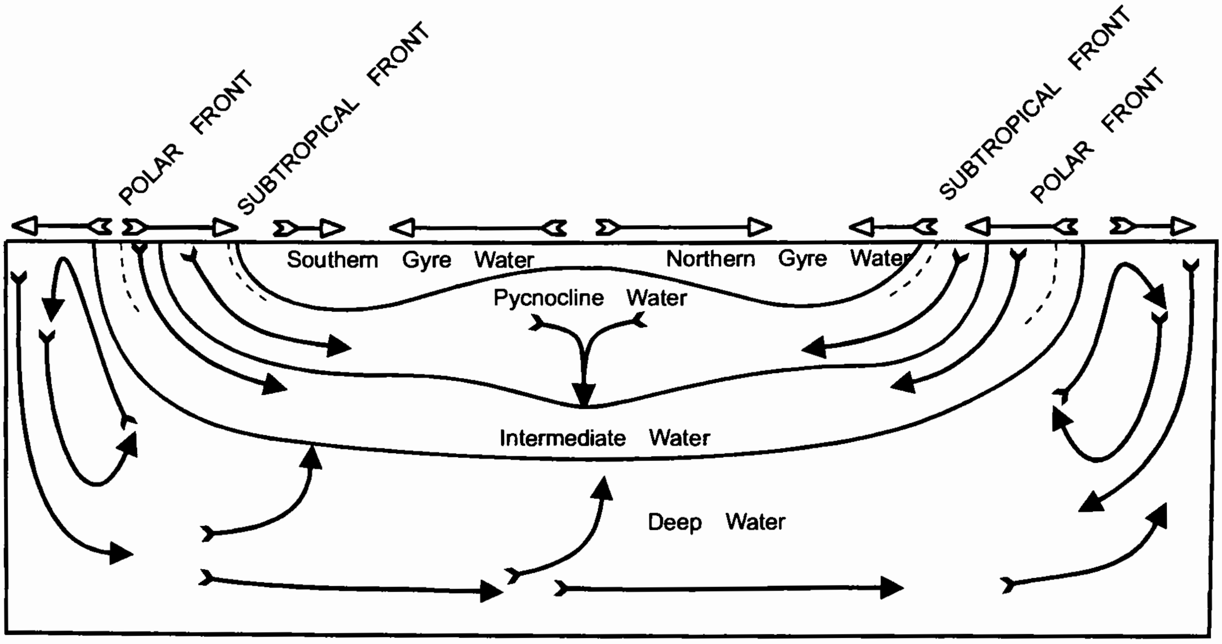

Fig. 9: Schematic representation of major ocean watermasses, showing the sites of their origin on the surface. Arrows with open heads along the surface indicate the meridional motion of the water induced by zonal winds.

about 1000 m are occupied by the main ocean thermocline, intermediate waters lie between 1000 and 2000 m, and deep and bottom waters extend from 2000 m to the ocean floor. Passages with depths less than 2000 m preclude flow of deep and bottom waters. Today the Antillean Arc prevents deep waters from entering the Caribbean Basin, but admits small amounts of Antarctic Intermediate Water. Shallow passages (< 500 m) connecting negative fresh-water balance seas (evaporation > precipitation + runoff) with the ocean, such as the Strait of Gibraltar and Straits of Bab El Mendab serve as point sources for introduction of warm saline intermediate waters into the ocean.

The thermohaline circulation of the ocean is small but important part of the ocean heat transport system, connecting high and low latitudes. Altering its flow would have regional or global climatic effects. Today, the cold saline deep waters that form in the polar regions and the cool, lower salinity intermediate waters that sink along the polar fronts are an important part of the global energy transport system, carrying cold water equatorward where it returns to the surface through the diffuse upwelling beneath the tropical-subtropical gyres and in the equatorial region. Reversals of the thermohaline system, with warm saline ocean deep waters forming in the tropics and flowing poleward (BRASS et al., 1982), would transport heat poleward into the relatively small polar regions, where it can become incorporated into the high-latitude deep convection. In the Mesozoic and early Cenozoic this may have been a more effective mechanism for warming the polar regions than heat transport by surface currents. However, for this system to operate efficiently there must be deep passages open into the ocean basins of the polar regions. The ability of the ocean heat transport system to warm the polar regions has generally been overestimated. BARRON (1983) calculated that the oceanic heat flux required to produce the warm Arctic temperatures of the Cretaceous and Paleogene would necessitate a water volume flow of about 112 Sverdrups (Sv) crossing the Arctic Circle. This is an enormous flow, compared to about 40 Sv for the Gulf Stream and about 3 Sv for the Norwegian Current today.

Plants

It is becoming evident that the evolution of land plants has played a major role in the development of climates during the Phanerozoic. Although there may have been plant life on land during the Proterozoic, perhaps in the form of cyanobacterial mats, vascular plants first appeared during the Silurian, and spread to cover much of the Earth's surface during the Devonian and Carboniferous. The vascular plants had an enormous effect on surficial geological processes. Acids secreted by the plants and the symbiotic fungi have increased the weathering rates for many mineral materials, but the effect of plant roots in binding together soil has reduced rates of erosion.

BERNER (1998) has postulated that the rise of land plants has had a major impact on the history of atmospheric oxygen and CO_2. The Carboniferous was a time of burial of very large masses of organic carbon. Every mole of carbon buried as organic matter results in a mole of molecular oxygen being added to the atmosphere. It is though that the massive burial of organic carbon during the Carboniferous was possible because organisms capable of decomposing lignin did not develop until the end of the Permian. Thus the woody lignin produced by Carboniferous plants did not rot and decompose, but was buried instead. This allowed a major draw-down of atmospheric CO_2 and a rise in atmospheric oxygen. The lower CO_2 content of the atmosphere is thought to have provided the condition necessary to initiate the Permo-Carboniferous glaciation of Gondwana.

Another possibility for plants to affect the climate system has occurred more recently though the spread of plants utilizing new photosynthetic pathways that alter the hydrologic cycle and change the atmospheric heat transport mechanisms.

Most trees and shrubs utilize the Calvin cycle to convert CO_2 and water vapor into organic matter via photosynthesis, releasing O_2. This process of consuming CO_2 and H_2O to produce organic matter and O_2 is termed carboxylation. The Calvin cycle involves an acid, phosphoglyceric acid, that contain three carbon atoms, hence the plants using this photosynthetic pathway are termed C3 plants. Unfortunately, enzymes involved in the photosynthesis also catalyze oxygenation of other compounds, consuming O_2 and releasing CO_2. The relative reaction rates of carboxylation to oxygenation depend on the atmospheric ratio of CO_2 to O_2, the temperature, and the brightness of the light. C3 plants have their maximum efficiency at high levels of CO_2, low levels of O_2, temperatures between 15 and 25°C, and medium illumination. Their efficiency decreases with decreasing levels of atmospheric CO_2, temperatures above 25°C, and in bright light. The decreasing levels of atmospheric CO_2 during the Cenozoic have resulted in decreased efficiency of CO_2 fixation by the C3 pathway. The limiting value for C3 plants, at which the carboxylation and oxygenation reactions are equal and there is no net fixation of CO_2 is probably between 150 and 50 ppm atmospheric CO_2 (CERLING, 1997). C3 plants typically have deep roots, and can tap the moisture in the deeper layers of soil. They play an important role in recycling water over land areas.

Fast-growing plants, such as maize and sugar cane, and many grasses, sedges, and some other plants typical of grasslands, savannas, and semi-arid regions utilize the Hatch-Stack cycle, a photosynthetic pathway which is markedly different from that of the C3 plants. These plants have a distinctive structure (Kranz anatomy), with the vascular tissue surrounded by a dense layer of bundle sheath cells with a high concentration of chloroplasts. Layers of mesophyll surround the bundle sheath cells. Different parts of the photosynthetic process take place in these different parts of the plant. The initial fixation of CO_2 takes place in mesophyll cells, where a 4-carbon acid, oxaloacetic acid, which is then reduced to malic acid, another 4-carbon compound. These acids give the name C4 to plants utilizing this pathway. The malate is then transported to bundle sheath cells, where it enters the chloroplasts and is oxidized to release CO_2. Then photosynthesis proceeds as in C3 plants. The extra step in the C4 pathway reduces its efficiency, but this loss is more than compensated for by an increased efficiency of carboxylation over oxygenation. The increased efficiency of carboxylation is achieved by enrichment of the CO_2 concentration in the bundle sheath cells until it is almost an order of magnitude higher than the atmospheric concentration (CERLING, 1997). The spread of C4 plants is regarded as an adaptation to the lowering of atmospheric CO_2 levels during the Cenozoic (EHRLINGER and MONSON, 1993), but they are also capable of much more rapid fixation rates than C3 plants. The most rapidly growing plants, such as maize and sugar cane are C4 plants. Because of their overall greater efficiency in fixing CO_2, C4 plants lose less water through transpiration per unit C fixed. Their maximum efficiency occurs at temperatures between 30 and 40°C and under bright light. Hence, C4 plants are adapted to warmer, drier, and brighter conditions. They typically have shallow roots and remove moisture only from the upper layers of the soil. Because of their efficient use of water and inability to use water from deeper soil layers, they have an important effect on the hydrologic cycle. They restrict the return of water to the atmosphere and promote drier conditions downwind.

Another group of plants, the Crassulaceae, cacti, euphorbias, and other succulents use a temporal separation of CO_2 uptake and photosynthesis (RICKLEFS, 1997) within the same cells. This modification of the photosynthetic pathway is termed crassulacean acid metabolism (CAM) The CAM plants open their stomata and take up CO_2 at night, when the temperatures are lower. During the hot day the stomata remain closed, conserving water. They are not as efficient at CO_2 fixation as either C3 or other C4 plants, but they can live under inhospitable conditions. CAM plants are especially adapted to semiarid and arid conditions, and include agaves, cacti, and other succulents. Their maximum efficiency occurs at temperatures around 35°C and under bright light. Their roots are usually restricted to shallow layers of the soil. Although they are a very minor component of the global biomass and have very low growth rates, their capability for water retention suggests that they may play a role in creating arid conditions.

DECONTO (1996) and HAY et al. (1997) noted that the atmospheric energy transfer system made much greater use of latent heat transport before the C4 and CAM plants appeared. DECONTO et al. (1998, 1999) believe that this is the explanation of a vexing problem in modeling a warm Earth. Even though CO_2 warms the polar regions effectively, simulations of the warm Cretaceous and Paleogene Earth were unable to produce an Asian continental interior warm enough in winter to correspond to interpretation of plant data from central Siberia. DeConto et al. found that by eliminating the C4 plants from the interactive vegetation component of the climate model, the winter temperatures in the interior of Asia increased to levels consistent with the plant data. The increase is due to an increased energy transport to the interior of the continent by the latent heat of water vapor. The greater amount of water vapor transported into the interior is the result of greater transpiration by C3 plants. The higher rates of evapotranspiration associated with C3 plants appear to have been the factor responsible for the lesser temperature gradients between the coasts and continental interiors in the past. Although the full history of C4 plants is not known, their spread around 8 Ma (CERLING, 1997) may have played a major role in modifying the earth's climate. It could be the major cause of the "Late Neogene climatic deterioration."

Summary

The many climatic states the Earth has experienced over its 4.5 billion year history are the result of changes in insolation, albedo, atmospheric greenhouse gas concentrations, paleogeography, and the evolution of vegetation, particularly that on land.

The energy radiated by the sun increases as it grows older. This effect has been compensated by a gradual decrease in atmospheric greenhouse gas concentrations. Cyclic changes in the Earth's orbital parameters affect the amount of radiation received from the sun at different latitudes over the course of the year. During the Quaternary, and probably during other times when the Earth was glaciated, the waxing and waning of continental ice sheets closely followed the changes in summer insolation at the latitude of the polar circle. The seasonal intensity of insolation in each hemisphere is governed by the precession and ellipticity of the Earth's orbit. At the polar circle the meridional minimum of summer insolation becomes alternately more and less pronounced as the obliquity of the Earth's axis of rotation changes. A variety of feedback processes amplify the insolation signals.

The naturally occurring greenhouse gasses (H_2O, CO_2, CH_4, O_3) modulate the insolation-driven climate and are probably responsible for the long-term history of climate change. Without the greenhouse effect the earth's surface would be frozen. In the Precambrian the weaker insolation was balanced by a much higher atmospheric content of greenhouse gasses, mostly the CO_2 that is now trapped in limestone and buried organic carbon. The CO_2 and H_2O have combined to weather silicate rocks in such a way as to act as a thermostat to maintain the earth's surface temperature between the freezing and boiling points of water. The reduction of atmospheric CO_2 concentrations during the Cenozoic is frequently cited as the cause of the general cooling of the planet since the middle Eocene.

The changing distribution of land and sea has altered the planetary albedo and affected the planet's uptake of energy from the sun and the pattern of its radiation back into space. The changing configurations of the ocean basins, and particularly interconnections between the oceans through narrow passages or gateways have altered the patterns of poleward ocean heat transport.

Plants have changed the planetary albedo and modified the greenhouse by consuming CO_2 and returning soil moisture to the atmosphere.

However, during the later Cenozoic many of the freely-transpiring C3 plants have been replaced by water-conserving C4 plants, mostly grasses, that have enhanced the global cooling trend and promoted desertification. Before the spread of C4 plants, the greater latent heat transport by water vapor into the continental interiors was a major factor in producing the equable climates of warm times.

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DISKUSSION

Die Klimaentwicklung im Verlauf der Erdgeschichte

KALLENBACH: Sie haben uns mit den Faktoren vertraut gemacht, die für die Klimaentwicklung Bedeutung haben und uns gleichzeitig einen Blick in die Vergangenheit gegeben. Das ist insoferne von großer Bedeutung, weil unsere rezente Klimabetrachtung ja nur einen ganz kurzen Zeitraum einnimmt und unsere Aussagemöglichkeiten für die Zukunft sind ja damit auch sehr beschränkt, das heißt der Blick in die Vergangenheit ermöglicht erst einen Blick in die Zukunft.

KERN: In der Kreidezeit sollen der CO_2-Gehalt und der Sauerstoffgehalt viel höher gewesen sein. Haben sie da aktuelle Daten? In der Literatur werden Sauerstoffgehalte von 27%, ja sogar bis 30% genannt und auch der CO_2-Gehalt war ein vielfaches des heutigen. Natürlich hängt das mit dem Klima und dem Pflanzenwuchs zusammen, denn je mehr Photosynthese, desto mehr Sauerstoff wird produziert.

Zur Frage der C_4-Pflanzen, ich habe das nicht ganz verstanden, mit der Ausbreitung der C_4-Pflanzen kann ich mir nur vorstellen, daß das Miozän gemeint ist; vorher kann es nicht gewesen sein, denn die C_4-Pflanzen haben ja Probleme bei ihren CO_2-Werten, da sie ja nicht konkurrenzfähig sind. Sie sind ja nur auf gewissen, engen Standorten, z.B. Wüstenstandorten, spezialisiert; sobald über 1% CO_2 erreicht wird haben sie große Probleme, denn dann gibt es Generalpflanzen (?), die konkurrenzfähiger sind, und in diesem Fall geht es ja darum, daß aus dem CO_2-Gehalt kein Konkurrenzvorteil erwächst.

HAY: Es gibt tatsächlich Hinweise, daß der CO_2-Gehalt in der Kreide höher war. Es gibt gewisse Bodenminerale, die darauf hindeuten und zwar in Wüstengebieten, wo kein organischer Kohlenstoffgehalt im Boden gewesen sein soll, das ist hauptsächlich von CERLING in Utah publiziert worden:

Für Sauerstoff kann man sagen, daß er der heutigen Atmosphäre entspricht, unter der Berücksichtigung, wieviel organischer Kohlenstoff begraben wird und wenn man organischen Kohlenstoff nicht wieder abbaut. Sauerstoff wird durch die Photosynthese produziert, d.h., wenn Sauerstoff produziert wird, dann wird auch organischer Kohlenstoff gebildet. Wenn dieser nicht wieder oxidiert wird, dann bleibt mehr Sauerstoff. Was man sagen kann: im Kimmeridge und in der Unterkreide sind riesige Mengen organischen Kohlenstoffes begraben worden, da sollte der Sauerstoffgehalt höher gewesen sein.

PREISINGER: Ich hätte zu dem Thema der Klimaschwankungen zwei Anmerkungen. Da sind einmal die MILANKOVIC-Zyklen, die auf den Erdparametern und den chaotischen Einflüssen der anderen Planeten beruhen und auch berechnet werden können, zur Zeit von Herrn LASCAR in Paris bis zurück auf 100 Millionen Jahre. Sind das eigentlich die einzigen Parameter, die den Lichteinfall von der oberen Erdatmsphäre ausmachen, oder gibt es auch noch kosmischen Staub und Variationen des kosmischen Staubes bis hin zu Asteroiden die hier einen Einfluß haben.

HAY: Es wurde von Gordon McDONALD u.a. in Californien vor zwei oder drei Jahren behauptet, es wäre noch einen vierten Mechanismus vorhanden. In der mittleren Ebene des Sonnensystems gäbe es eine ganz dünne Staubschicht. Die Erdlaufbahn ist geneigt, aber das ändert sich mit einem 100.000-Jahre Zyklus und sie geht durch diese Mittelebene. Das ist aber alles ziemlich hypothetisch.

PREISINGER: Diese Schwankungen des Immer-Eintauchens in den Asteroidenstaubwind sind aber in den letzten zehn Jahren über Satelliten gemessen worden. Es gibt aber zusätzlich auch noch die Möglichkeit, daß sich die Einstrahlung durch andere Staubsysteme zwischen 400 und 500 Watt pro m^2 auf einen bestimmten Ort der Erde zusätzlich verändert. Es wird sich ja in der nächsten Zeit herausstellen, wenn diese Rechnungen von Herrn LASCAR im Dezember fertig sind, daß wir überprüfen können, speziell an den genauen Untersuchungen an der KT-Grenze, ob tatsächlich diese rhythmischen Störungen rein auf die MILANKOVIC-Zyklen, um ein Schlagwort zu nennen, zurückzuführen sind.

Eine zweite Bemerkung hätt ich noch: ein Charakteristikum der Kreide war, daß es Ost-West - Meere gegeben hat und keine Nord-Süd - Meere wie heute, was den Verlauf des Kaltwasserstromes und damit des Klimas schon sehr wesentlich beeinflußt. Können sie über den Beitrag dieser Ost-West - Strömung etwas sagen ?

<u>HAY:</u> Man könnte annehmen, daß die mehr zentrale Strömung höhere Temperaturunterschiede zwischen den polaren Zonen und den Tropen verursachen würde als die meridionale Transport durch den Ozean.. Aber das scheint nicht der Fall zu sein. Die Situation, die wir heute haben, wo Wasser im norwegisch-grönländischen Meer absinkt und der Nordatlantik, also der Golfstrom, nach Norden gezogen wird und Europa dabei erwärmt, das ist etwas ganz merkwürdiges und global gesehen relativ klein, wenn man indes die großen Eismassen betrachtet, die sich während des Glazials bilden, die sind alle um den Nordatlantik arrangiert, und das heißt, das ist eine Funktion der Feuchtigkeit, denn im...(unverständlich)... war das Wasser dort warm. Das ist ein begrenztes Gebiet, aber es hat doch eine globale Wirkung.

<u>PREISINGER:</u> Im Prinzip gehen wir davon aus, daß die Sonneneinstrahlung gar nicht konstant ist. Was sagt die Sonnenforschung ? Gibt es da in der Erdgeschichte irgendwelche Schwankungen in der Emission der Sonne ?

<u>HAY:</u> Das ist eine interessante Frage. Da gibt es das Neutrinoproblem. Nach der heutigen Theorie, wie die Sonne Energie erzeugt, müßte eine Flux von Neutrinos durch die Erde kommen. Man hat versucht, das zu messen und man hat fast keine gefunden, sodaß sich die Frage erhoben hat, ob die Sonne im Moment überhaupt läuft ? Denn die Photonen brauchen im Gegensatz zu Neutrinos ca. 6 Mio Jahre, um von der nuklearen Reaktion in der Sonnenmitte bis zu ihrer Oberfläche zu gelangen, obwohl sie von dort dann in 8 Minuten auf der Erde sind. Es kann sein, daß das System in der Mitte der Sonne derzeit nicht läuft.

Zunächst hat man gemeint, es muß ein Problem mit dem Meßverfahren gewesen sein. Vor zwei Jahren hat man das neu untersucht, da braucht man Kohlenstofftetrachloridbehälter, ganz tief vergraben, und dann ist man zum Schluß gekommen, es liegt nicht an dem Verfahren, sondern der Neutrinoflux ist nicht das, was man erwartet hat. Möglicherweise versteht man nicht ganz, wie die Sonne Energie erzeugt.

Es gibt Fluktuationen, aber wahrscheinlich sind sie nicht zu beobachten, weil die Photonen solange brauchen, und die gehen in verschiedene Richtungen.

<u>PREISINGER:</u> In letzter Zeit hat man mit der C14-Methode gezeigt, daß Kohlenstoff nicht konstant erzeugt wird, und damit ist die Absolutdatierung etwas problematischer geworden. Wenn man diese Schwankungen in den letzten paar tausend Jahren ansieht -mehr kann ich nicht beurteilen dann ist das echt typische kosmische Strahlung, die von der Sonne kommt, und die Schwankungen weisen Rhythmen von 30 - 50 Jahren auf, das kann man heute schon nachweisen.

<u>KALLENBACH:</u> Eine Frage, was die Sonneneinstrahlung betrifft: besonders im Sommer und auf den Polkappen ist den Energieimpuls extrem hoch. Aber wie steht das mit dem Einstrahlwinkel ? Für mich ist das nicht ganz einsichtig, wir haben ja sehr flache Einstrahlwinkel, das müßte eigentlich die Energiebilanz verringern.

<u>HAY:</u> Das ist darin schon berücksichtigt

<u>KERN:</u> Bezüglich Sonnenstrahlung: Sicher, bis alle Photonen die Sonnenoberfläche erreichen, das dauert einige Zeit, aber die Sonnenfleckenaktivität hat man historisch verglichen; in der "kleinen Eiszeit" hatten wir keine Aktivitäten, und jetzt sehen wir einem Maximum entgegen, und das wird von einigen Autoren als möglicherweise eine Starthilfe für Eiszeiten oder Warmzeiten gesehen.

<u>SCHROLL:</u> Wir sollten die vulkanischen Erscheinungen, ganz gleich, wie sie zustande

kommen, nicht außer acht lassen. Hier kommt es ja zu einem enormen Ausfall an CO2, der in den Karbonatgesteinen gespeichert ist, oder Karbonatitbildungen, durch die riesige Mengen von CO2 wieder ausgeschlossen werden.

HAY: Vulkane sind vor allem wichtig durch den Ausstoß von SO2, das ein Aerosol und relativ opak ist, und offenbar einen klimatischen Effekt hat. Allerdings gibt es eine ganz interessante Studie von U. ELSASSER, einem Klimatologen in Noah, USA, der vulkanische Eruptionen und Klima, besonders Abkühlungen, genau untersucht hat, und der hat eine bessere Korrelationen dafür gefunden, daß es eher nach einer Abkühlung eine vulkanische Eruption gibt als umgekehrt. Das hat er leider nie so richtig publiziert, aber das war so.

In der jungen Erdgeschichte, seit 10, aber besonders seit 5 Mio Jahren, gibt es eine Zunahme der Vulkanizität, das kann man mit Aschenmengen im Pazifikbecken nachweisen. Dann ist die Frage, was hat das mit Klimaänderungen zu tun und wie funktioniert das, aber eigentlich weiß man nicht sehr viel davon.

RIEHL - H.: Diese thermische freie Zeit oder überhaupt voll eisfreie Zeit, könnte das mit einem Meteoritenereignis in Zusammenhang stehen ? Die Perm-Trias-Grenze ist eine der großen Grenzen und wir haben voriges Jahr diskutiert, ob damals ein solches Ereignis möglich gewesen wäre, ähnlich dem Chixculub - Ereignis an der KT - Grenze.

HAY: Die Enteisung im Paläozoikum geschieht im Mittelperm, vor der Faunengrenze, und für diese hat bis jetzt niemand etwas wirklich Zutreffendes für einen Meteoriteneinschlag gefunden. Aber was ganz merkwürdig da ist, ist die starke Verbeitung von Fungien, gerade an der Grenze ist z.B. Holz immer sehr stark von Pilzen angegriffen, und da kommt die Frage, ob wir da einfach eine Erfindung dieser Pflanzen sehen, daß die einfach entdeckt haben, wie man Holz abbaut, und dadurch viel CO2 in die Atmosphäre abgegeben haben und daß das alles verändert hat, aber ich habe keine Ahnung davon.

PREISINGER: Es wurde die Frage angeschnitten, ob ein Impakt eines Meteoriten oder eines anderen kosmischen Körpers eine Vereisung auslösen kann. Ich würde glauben, daß das an der KT-Grenze wohl stattgefunden haben könnte, aber höchstens für ein paar hundert Jahre.

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