b33 The Milankovitch insolation hypothesis for climatic cycles < chaos; 1940s, eccentricity, obliquity, precession >

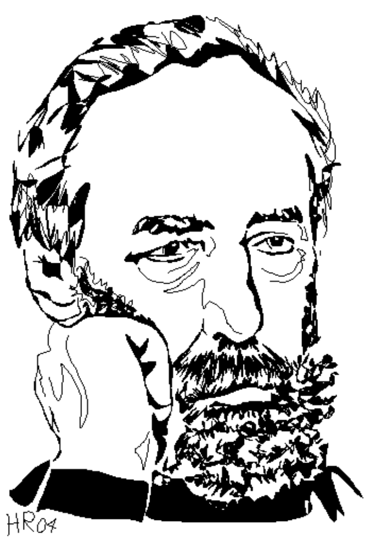
> The butterfly effect ... The phrase comes from the title of a [1972 talk: "Predictability: Does the Flap of a Butterfly's Wings in Brazil Set off a Tornado in Texas?" by Edward Lorenz [1917-2008]. The idea is that in a chaotic system, small disturbances grow exponentially fast, rendering [and this is the downside implicit in the word chaotic] long-term prediction impossible. ... [for a billiard ball this is after 11 collisions].[1] The Lyapunov time sets a horizon beyond which acceptable prediction becomes impossible ... for the solar system [this is 2-230] million years. —Steven Strogatz *SYNC*, 2003.[2]

Newton (1643-1727) worried that the behavior of the solar system (a many-body problem in celestial mechanics) is inherently chaotic and, for it not to fly apart, he postulated that God intervenes every now and then to aright things. Stability in the long term has "no need of that hypothesis," Laplace (1749-1827) proved, using perturbation theory that he invented, as the eccentricities and inclinations of planetary orbits to each other always remain small, constant, and self-correcting. This result, first read before the French Academy in 1773 [3] and included in his *Celestial Mechanics treatise*, 1786,[4] begins by assuming that there is only one major source of gravity and that all the other forces are minor, though persistent.[5] Modern analysis of the dynamical behavior of Earth-Sun-Moon system yields in decreasing cycle-durations of climatic influence the following: [6]

100,000 year **eccentricity of the orbit (ellipse) cycle**
This is a rough average of 95,000 and 123,000 year orbit cycles, and subsidiary oscillations at periods ranging from 50,000 to 1.9 million years due to gravitational perturbations mostly caused by Venus. Currently in its orbit, Earth on January 3 is at perihelion (closest to Sun at a distance of 91.4 million miles) and on July 4 is at aphelion (furthest from Sun at a distance of 94.5 million miles). This difference in distance between perihelion and aphelion varies insolation (solar energy that Earth receives) presently by 7% (e = 0.0174, see ***Figure b33.1***). When Earth's orbit is at its most elliptical (e = 0.06), difference in distance between perihelion and aphelion varies insolation by 17%.[7]

41,000 year **obliquity (tilt) cycle**
Tilt is the angle between Earth's rotation axis and Earth's orbital axis which is perpendicular (normal) to the ecliptic (Earth's orbital plane) (***Figure b33.2***). Earth's seasons are the result of tilt.

22,000 year **precession of the equinoxes (wobble) cycle** (discovered by Hipparchus ca. 150 BCE)
The moving North celestial pole in its precession, compounded of a 23,000 year major cycle and a 19,000 year minor cycle, points (at rare intervals) to the vicinity of a "north star" (***Figure b33.2***).



Hypotheses to explain the Ice Age glacials and interglacials by insolation variations historically have drawn upon the independent work of astronomers. Formulas that allow the changing orbital shape and the axial precession of the planets to be calculated were originally published by planet Neptune discoverer (in 1846) Urbain Le Verrier (1843-1855).[8] Beginning in 1864, **James Croll** (1821- 1890) (who should be remembered for revealing [9] the nonsensical nature of Matthew Fontaine Maury's physics in *Paper on the Gulf Stream and currents of the sea*, 1844,[10] and indeed all his works) used these formulas to graph the changes of Earth's orbital eccentricity for the past 3 million years.[11] He found that cycles of high eccentricity follow upon each other for hundreds of thousands of years and then cycles of low eccentricity become the pattern as is the case today and calculably was so for the last 10,000 years. A planet orbits farthest from its star at apoapsis and nearest at periapsis. The ratio of the difference of these distances to their sum is the eccentricity. Earth's present eccentricity is about 0.0174 and its highest eccentricity for a time during the last glacial was about 0.058.

Le Verrier had shown that the total amount of Earth-received solar energy (insolation) in a year will add to almost the same regardless of eccentricity. So “high” (large) eccentricity is not enough to account for a glacial. But Croll realized the importance of calculating *when* during the year the heat arrived. When the winter *season* and apogee (Earth farthest from Sun) coincide during an epoch of high orbital eccentricity, winter will be prolonged. This will be so for, by comparison to its racing speed at perigee, Earth at apogee ambles along its orbit making the time of all seasons there longer, and in the winter hemisphere a longer lasting snow accumulation will in turn prolong its winter by keeping that hemisphere’s albedo (reflectivity) high. This amplifying effect, James Croll claimed, triggered the growth of ice sheets. At times of low eccentricity such as exists today winters are evidently of too brief for low-latitude snow accumulations to last into summer and induce a glacial.

Croll’s hypothesis takes into account the precession of the equinoxes cycle and variations in the shape of Earth’s orbit. It predicts that in epochs when Earth’s orbit is markedly elongate and a solstice and apogee are concurrent, glacial conditions will be in the hemisphere that is near midwinter at apogee. At the same time, an ice sheet will not exist in other hemisphere. This latter provided for a possible test: If it could be shown that glacials are concurrent in the two hemispheres, Croll’s hypothesis would be disproved.

Geologists (as Archibald Geikie who with his brother James authored *The Great Ice Age*, 1874) looked at the top layer of glacial till in each hemisphere to estimate its age from how much it had weathered.[12] They found little weathering. This implied that little time has elapsed since the end of the Ice Age. But this held for glacials in *both* hemispheres. Still, those who would support Croll’s hypothesis could investigate how climatic variables that slow or speed weathering, such as water availability, sediment porosity, average temperature, and so on, might have operated differently in each hemisphere since the Ice Age. Interest, however, waned in the absence of definitive data. James Dana’s textbook, *Manual of Geology*, 1894, summation was that “there is no evidence yet reported that the Glacial periods of the two hemispheres were not essentially simultaneous in their epochs.”[13] In fact, the glacials were simultaneous (as the deepsea sedimentary record attests).

What is missing in Croll’s analysis, is found in *insolation theory*, developed in the 1940s by **Milutin Milankovitch** (1879-1958), which has as a prediction the observed periodicity (but not the magnitude of) the temperature variations.[14] Milankovitch could show that the tilt of Earth’s axis is a key player in what may trigger a glacial. If Earth’s axis had no tilt, then the poles would always be in a winter (glacial) condition. This is easy to understand. Interestingly, if Earth’s axial tilt is 54°, then amounts of sunlight radiated to every place on Earth would, in the course of a year, add to the same. This latter result needs to be calculated as it is not immediately obvious. A tilt of 58° or more would allow continental glaciers to form at sealevel at the equator when none would necessarily form at the poles.

The obliquity (tilt) of Earth’s axis, that is 23½° today, cycles every 41,000-years between a maximum of 25° and a minimum of 22°. In 1938, Milankovitch published graphs that show radiation curves for summer-time insolation. These show, at 15° and 45° North latitude, the effect on insolation of the 22,000-year precession of the equinoxes cycle (studied by Croll) will be strongly apparent. The same effect does not show at 75° North latitude. But dominant there is the effect of the 41,000-year obliquity (tilt) cycle *which could cause a glacial simultaneously in both hemispheres*.

Milankovitch had used for his astronomical calculations the mathematical solution for the behavior of the planets published in 1904 by Ludwig Pilgrim. The climatologist Wladimir Peter Köppern in the 1920s collaborated and gave him a method for calculating the radiation at any given latitude and season. In *Astronomical Methods for Investigating Earth’s Historical Climate*, 1938,[15] and *Canon of Earth irradiation and its application to the Ice Age problem*, 1941,[16] Milankovitch went beyond merely providing geologists with calculated radiation curves for selected latitudes. He had formulated a mathematical relationship between summer radiation and the altitude of the snowline. The altitude of the snowline would presumably be zero (sea-level) near the minimum extent of an ice sheet.

Geologists now had a graphs from which could be obtained, theoretically, the latitude of the ice sheet edge for any time. Milankovitch graphs showed such details for the past 650,000 years. The 41,000 obliquity cycle is well recorded by benthic foraminiferal proxies: oxygen isotope ratios for global ice volumes, and Mg/Ca ratios for bottom water temperatures.[17] Thomas M. Cronin has found that diversity of ostracod benthic species is strongly correlated.[18]

To establish the relevance of the Milankovitch hypothesis to an understanding of climate variations, biofeedback mechanisms (Gaia) need to be identified that link to orbital variations. One that J. D. Hays meaningfully calls a "pacemaker," would trigger large long-term climate pulses.[19] For example, in the interval between 5,000 and 12,000 years ago, the Sahel and Sahara had a wetter climate as evidenced by sediments of then lakes and pollen types in these. Milankovitch climatic forcing can account for some of the climatic difference via increased land-ocean temperature contrast and enhanced monsoons. However, according to John E. Kutzbach, most of the climatic difference then follows (from modeling) when desert is replaced by grassland and desert soils are replaced with more loamy soil. In such soils, a variety of fungi can exist that by potassium delivery and take up of carbon dioxide symbiotically promote high diversity and production of grasses and woodlands.[20]

In open tropical oceans (where sea temperature and salinity is not greatly different between glacial and interglacial chrons), oxygen isotope variation is almost all attributable to changes in global ice volume and sea level. But there, precise dating of oxygen isotope records (in $CaCO_3$ of coral and foraminerfera) is limited to the range of 30,000 years by the short half-life of radiocarbon. On the hypothesis that orbital variations of insolation at 60°N and ice sheet volumes are closely linked in time, J. Imbrie, beginning in 1992, constructed an extend timescale (SPECMAP) for the oxygen isotope record in marine plankton shells in cores of North Atlantic seafloor sediments. The timescale of Northern astronomical-forcing predicts, for example, that 127,000 years ago the second-to-last (penultimate) glacial ended.[21] However, this same date in *northern* ice core data (in which the precise age in years is known by counting yearly layers) accords with the marine recorded *midpoint* of the greatest cold of the penultimate glacial. By contrast, G. M. Henderson and N. C. Slowey in 2000 found that the penultimate glacial midpoint was 135,000 years ago.[22] This much older date relies on a method of accurate uranium-thorium dating of the marine calcareous sediments (to the *south*) back through 500,000 years (***Figure b33.3***). The implication is that ice-age cycles are driven by orbital variations in solar irradiance either in the tropics or in the Southern (not Northern) Hemisphere.

The greater Earth's tilt, the more extreme the seasons but, somewhat counter intuitively, climate modeling coupling atmosphere circulation and ocean currents finds, for the build up of continental ice sheets, times when the tilt has been least. The milder summers allow for the existence of more extensive low-altitude snow fields. Low tilt (22.404°) and high eccentricity (0.041421) is calculated from the Milankovitch curves to have been 115 thousand years ago. ❑

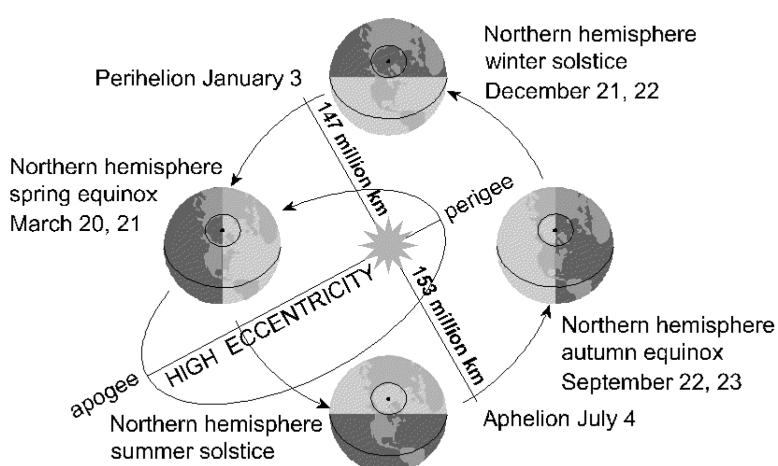


Figure b33.1

Earth's orbit is presently with low eccentricity (0.0174 nearly its minimum 0.005, which is an orbit that is near to being a Sun-centered circle, e = 0). As the length (p) of the year stays the same, the length (d) of the semi-major axis of Earth's elliptical orbit stays the same as eccentricity (e) changes (Sun stays at one focus). This accords to Kepler's 3rd law: p^2/d^3 = a constant.

Note: e is not in the above formula. So, a changing value of e leaves unchanged the length of the year. However, Kepler's laws describe reality only approximately.

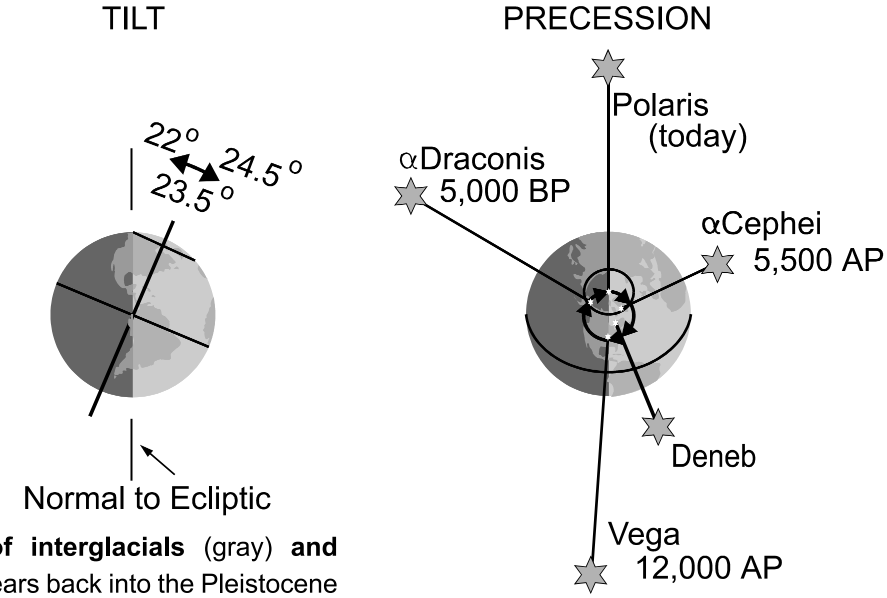
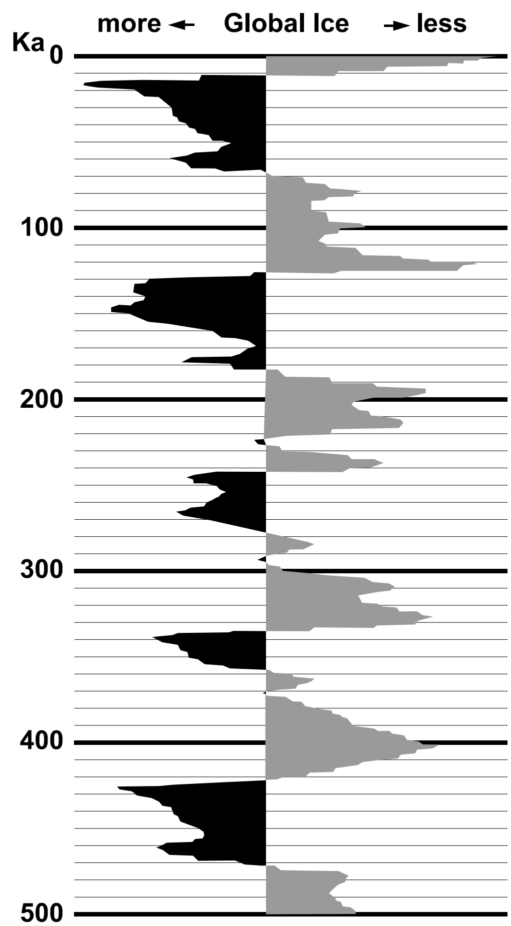


Figure b33.2
The Arctic Circle and Equator is shown on these two views of Earth (at N. summer solstice) for the tilt illustration (left) and (at N. autumn equinox) for the precession illustration (right).

Note: Earth's tilt is 23.44 degrees presently.

The precession of the North Celestial Pole is clockwise.

Figure b33.3 **Times of interglacials** (gray) **and glacials** (black) for 500,000 years back into the Pleistocene Ice Age that began 2,588,000 years ago.



Temperatures at Earth's surface, and levels of CO_2 in the atmosphere, have *risen* during interglacials and have *fallen* during glacials. This certain finding was reported by J. M. Barnola in 1987.[23] But inconvenient for prognostication, which be the cause for the effect remains uncertain.

Where, because of a lack of the iron needed for their photosynthesis, phytoplankton fare poorly, unused CO_2 leaks from ocean to atmosphere. This happens today from the nutrient-rich sunlit ocean surface around Antarctica south of the polar front (the Southern Ocean), and could be typical of interglacials.

In 2002, M. A. Brzezinski and M. Matsumoto proposed that the known to be dustier atmosphere during glacials, delivers iron to what, during interglacials, are iron deficient areas of the oceans.[24] Then the sinking of phytoplankton (which have a negative buoyancy) would result in a net transfer of CO_2 back to deep water in the Southern Ocean. Iron (sulfate) fertilization trials in 2002 showed that each atom of iron causes such sequestering of between 10,000 and 100,000 atoms of carbon and scaled could absorb 15% of the present atmospheric CO_2 build-up. (Isolating the deep waters from the atmosphere by capping them with pack ice at the surface would have the same effect.) But no panacea: the algal blooms vent methyl bromide, an ozone poison,[25] and also bourgeoning numbers of plankton grazers effectively soon stop any CO_2 sequestration.[26]

East Antarctica ice sheet margins have continuously flowed out upon the ocean to calve during 100,000-year period glacial interglacial cycles since a mid-Pleistocene transition (700,000-1,250,000 yrs ago) before which, beginning 2,588,000 yrs ago, 40,000-year period glacial interglacial cycles were the norm. Significantly different then was that the ice margins of a fluctuating-in-area Antarctica ice sheet did not reach the coast.[27]