Lecture notes for Tuesday 17th March 2020 class

MSc (IV) semester: Paper-9 Atmosphere and Global Climate Change

(Dr. Swati Diwakar)

Topic that was to be covered in the lecture was:

Milankovitch (Orbital) Cycles and Their Role in Earth's Climate

Subtopics:

1) Milutin Milankovitch: life and contribution in estimating past climate
2) Orbital cycles/variations
3) Changes in the Eccentricity of the Earth’s Orbit
4) Changes in the Obliquity of the Earth’s Axis
5) Precession of the Earth’s Axis of Rotation
6) Effects of the Milankovitch Cycles

I have attached relevant study material for the above topics from the references mainly:

1) Jacobson, M. Z., & Jacobson, M. Z. *Atmospheric pollution: history, science, and regulation*. Cambridge University Press.
   Chapter 12:The greenhouse effect and Global warming (pages 331-334)

2) Wallace, J. M., & Hobbs, P. V. (2006). *Atmospheric science: an introductory survey* (Vol. 92). Elsevier.

Some important webpages you can visit for understanding the Milankovitch cycles are as follows:

1. NASA Global Climate Change

https://climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate/

2. NASA Earth Observatory

https://earthobservatory.nasa.gov/features/Milankovitch/milankovitch_2.php when summer insolation at high northern latitudes is strong.[21]

The orbital variations believed to be responsible for these pronounced climatic swings involve:

i. 100,000-year cycle in *eccentricity* (the degree of ellipticity, defined as the distance from the center to either focus of the ellipse divided by the length of the major axis), which ranges from 0 to 0.06 and is currently 0.017,
ii. 41,000-year cycle in the *obliquity* (i.e., the tilt of the Earth's axis of rotation relative to the plane of the Earth's orbit) which ranges from 22.0° to 24.5° and is currently 23.5°, and
iii. 23,000- and 19,000-year cycles in the *precession* of the Earth's orbit. As a result of the precession cycle, the day of the year on which the Earth is closest to the sun (currently January 3) progresses through the year at a rate of ~1.7 calendar day per century.[24]

Figure 2.33 shows a schematic visual representation of these three types of orbital perturbations. When the eccentricity and obliquity are both near the peaks of their respective cycles, summertime insolation at 65 °N varies by up to ~20% between the extremes of the precession cycle (see Exercise 4.19).

In Fig. 2.34 a time series of the rate of growth of the continental ice sheets, as inferred from oxygen-18 concentrations in marine sediment cores, is compared with a time series of summertime insolation over high latitudes of the northern hemisphere, as inferred from orbital calculations. The degree of correspondence between the series is

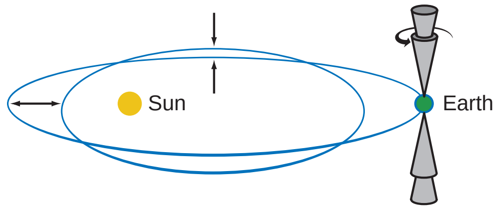

Fig. 2.33 Schematic of the Earth's orbital variations. The precession cycle in the tilt of the Earth's axis is represented by a single cone; the cycle in the obliquity of the axis is represented by the presence of two concentric cones, and the extrema in the ellipticity of the orbit are represented by the pair of ellipses. The figure is not drawn to scale. [Adapted from J. T. Houghton, *Global Warming: The Complete Briefing*, 2nd Edition, Cambridge University Press, p. 55 (1997).]

quite striking. The fit can be made even better by synchronizing the maxima and minima in the oxygen-18 record with nearby features in the insolation time series.[25]

2.5.4 The Past 20,000 Years

The transition from the last glacial to the current interglacial epoch was dramatic. The ice sheets started shrinking around 15,000 years ago. By 12,000 years ago the Laurentide ice sheet was pouring huge volumes of melt water into newly formed lakes and rivers, setting the stage for a series of flood events that shaped many of the features of today's landscape. Around this time the emergence from the ice age was interrupted by an ~800 year relapse into ice age conditions, an event referred to by geologists as the *Younger Dryas*.[26] The signature of the Younger

[21] Many of the elements of the orbital theory of the ice ages are embodied in works of James Croll,[22] published in 1864 and 1875. In 1920, Milutin Milankovitch[23] published a more accurate time series of insolation over high latitudes of the northern hemisphere based on newly available calculations of the variations in the Earth's orbit. Wladimir Köppen and Alfred Wegener included several of Milankovitch's time series in their book *Climates of the Geologic Past* (1924). The idea that summer is the critical season in determining the fate of the continental ice sheets is widely attributed to Köppen. Analysis of extended sediment core records, which did not become widely available until the 1970s, has provided increasingly strong support for orbital theory.

[22] **James Croll** (1821–1890). Largely self-educated Scottish intellectual. Variously employed as a tea merchant, manager of a temperance hotel, insurance agent, and janitor at a museum before his achievements earned him an appointment in the Geological Survey of Scotland and substantial scientific recognition.

[23] **Milutin Milankovitch** (1879–1958). Serbian mathematician. Professor, University of Belgrade.

[24] Evidence of the precession cycle dates back to the Greek astronomer, **Hipparchus**, who inferred, from observations made more than a century apart, that the axis around which the heavens rotate was slowly shifting.

[25] The relationship between depth within the core and time depends on the rate of sedimentation, which varies from one site to another and is not guaranteed to be linear. Hence, in assigning dates on the features in the cores, it is necessary to rely on supplementary information. The reversal in the polarity of the Earth's magnetic field, which is known to have occurred 780,000 years ago and is detectable in the cores, provides a critical "anchor point" in dating the sediment core time series.

[26] *Dryas* is a plant that currently grows only in Arctic and alpine tundra, fossil remains of which are found in a layer of sediments from northern Europe deposited during this interval. *Younger* signifies the topmost (i.e., most recent layer in which dryas is present).

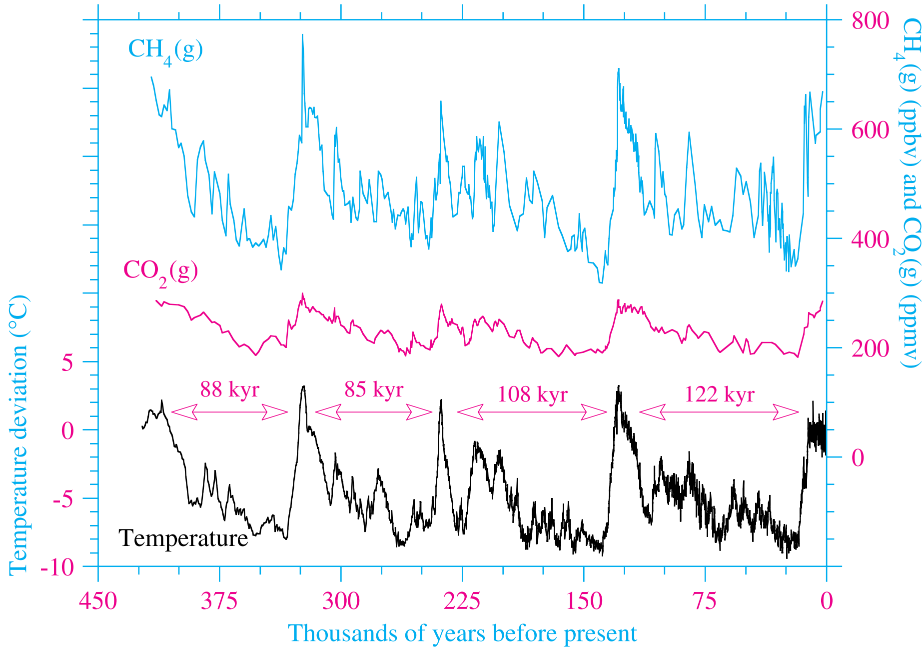

Figure 12.16. Temperature, methane, and carbon dioxide variations from the Vostok ice core over the past 420,000 to 450,000 years. Sources: Jouzel et al. (1987, 1993, 1996); Petit et al. (1999). Temperature variations are relative to a modern surface–air temperature over the ice of −55°C.

ice sheets occurred with a period of about 40,000 years (Shackleton and Opdyke, 1976). During the past 700,000 years, such advances and retreats have occurred with periods of about 100,000 years. The reasons for the 100,000-year cycle can be elucidated from Fig. 12.16.

Figure 12.16 shows the temperature trend over the past 450,000 years, a period covering nearly one-quarter of the Pleistocene epoch. The figure also shows carbon dioxide and methane trends over the past 420,000 years. Data for the table were obtained from the Vostok, Antarctica, ice core. To date, drilling of the Vostok ice core has extended down to a depth of more than 3.6 km. Data from the core enabled the reconstruction of 450,000 years of atmospheric history.

Figure 12.16 shows that the Earth has gone through four glacial and interglacial periods during the past 450,000 years. Within these major periods are minor periodic oscillations. The major and minor temperature oscillation can be explained, for the most part, in terms of three cycles related to the Earth's orbit, called **Milankovitch cycles**. Milankovitch cycles are named after Serbian astronomer **Milutin Milankovitch** (Milankovitch, 1930, 1941). They are caused by gravitational attraction between the planets of the solar system and the Earth. Milankovitch was the first to calculate the effects of these cycles on incident solar radiation reaching the Earth. The cycles are discussed briefly next.

Changes in the Eccentricity of the Earth's Orbit

Figure 12.17 shows that the Earth travels around the sun in an elliptical pattern, with the sun at one focus. In the figure, *a* and *b* are the lengths of the major and minor semiaxes, respectively. The distance between the center of the ellipse (point C) and

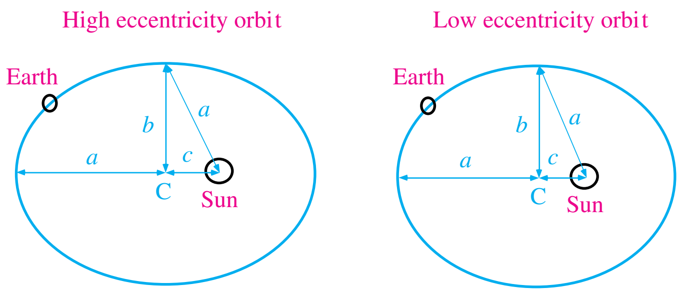

Figure 12.17. Earth's orbit around the sun during periods of high and low orbital eccentricity. The eccentricities are exaggerated in comparison with real eccentricities of the Earth's orbit.

either focus is c, which is related to a and b by the Pythagorean relation, $a^2 = b^2 + c^2$. The **eccentricity** (e) of the ellipse is

$$e = \frac{c}{a} \tag{12.7}$$

The eccentricity varies between 0 and 1. A circle has an eccentricity of 0. Earth's eccentricity is currently low, 0.017 (Example 12.2), indicating that the earth's orbit is nearly circular but noncircular enough to create a 3.3 percent difference in distance and a 6.6 percent difference in incoming solar radiation between June and December.

EXAMPLE 12.2

Calculate the current eccentricity of the Earth.

Solution

Figure 12.1 shows that the Earth-sun distance during the winter solstice (when the Earth is closest to the sun) is currently $a - c = 147$ million km and that during the summer solstice (when the Earth is furthest from the sun) is $a + c = 152$ million km. Solving these two equations gives $c = 2.5$ million km and $a = 149.5$ million km. Substituting these numbers into Equation 12.7 gives the current eccentricity of the Earth's orbit around the sun as $e \approx 0.017$.

The eccentricity of the Earth varies sinusoidally with a period of roughly 100,000 years. The minimum and maximum eccentricities during each 100,000-year period vary as well. The minimum eccentricity is usually greater than 0.01 and the maximum is usually less than 0.05. Whereas today the Earth is in an orbit of relatively low eccentricity, in 50,000 years it will be in an orbit of high eccentricity. During orbits of high eccentricity, the Earth–sun distance can be about 10 percent greater in June than in December, and the incident solar radiation can be about 21 percent less in June than in December. Today, the Earth–sun distance is about 3 percent greater in June than in December, and incident solar radiation is about 7 percent less in June than in December.

Because the yearly averaged distance of the Earth from the sun is less in a period of low eccentricity than in a period of high eccentricity, yearly averaged temperatures are higher in periods of low eccentricity than in periods of high eccentricity. This can be seen in Fig. 12.16, which shows that natural interglacial temperature maxima occurred 122,000, 230,000, 315,000, and 403,000 years ago, all times of low eccentricity.

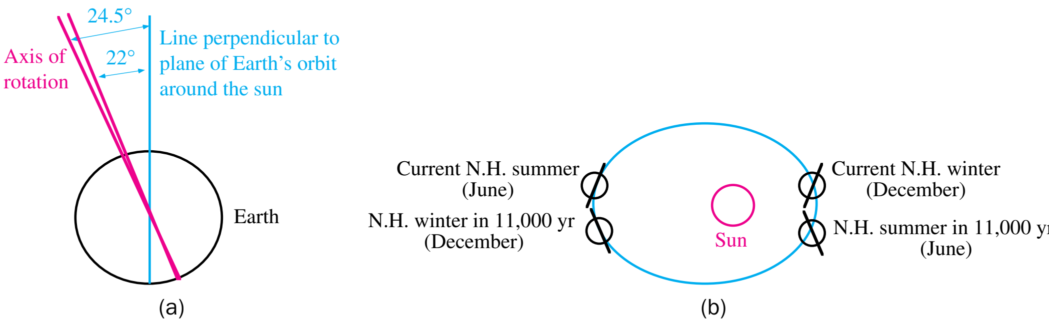

Figure 12.18. Changes in the (a) obliquity of the Earth's axis of rotation and (b) precession of the Earth's axis relative to a point in space.

Changes in the Obliquity of the Earth's Axis

The **obliquity** of the Earth's axis of rotation is the angle of the axis relative to a line perpendicular to the plane of the Earth's orbit around the sun. Figure 12.18(a) shows the variation in the Earth's obliquity. Every 41,000 years, the Earth goes through a complete cycle where the obliquity changes from 22° to 24.5° and back to 22°. Currently, the obliquity is 23.5°, in the middle of a cycle. When the obliquity is low (22°), more sunlight hits the equator, increasing south–north temperature contrasts. When the obliquity is high (24.5°), more sunlight reaches higher latitudes, reducing temperature contrasts. Thus, the obliquity affects the seasons and temperatures at each latitude on Earth. Superimposed on the large temperature variations seen in Fig. 12.16 are smaller variations, some resulting from changes in obliquity.

Precession of the Earth's Axis of Rotation

Precession is the angular motion (wobble) of the axis of rotation of the Earth about an axis fixed in space [Fig. 12.18(b)]. It is caused by the gravitational attraction between the Earth and other bodies in the solar system. Currently, the Northern Hemisphere is further from the sun in summer than in winter. In 11,000 years, angular motion of the Earth's axis of rotation will cause the Northern Hemisphere to be closer to the sun in summer than in winter. The complete cycle of the precession of the Earth's axis is 22,000 years. Precession of the Earth's axis does not change the yearly or globally averaged incident solar radiation at the top of the Earth's atmosphere. Instead, it changes the quantity of incident radiation at each latitude during a season. In 11,000 years, for example, Northern Hemisphere summers will be warmer and Southern Hemisphere summers will be cooler than they are today. Because seasonal changes in temperature result in yearly averaged changes in temperature at a given latitude, some of the cyclical changes in temperatures seen in the Antarctic data shown in Fig. 12.16 are due to changes in precession.

Effects of the Milankovitch Cycles

The Milankovitch cycles appear to be responsible for the cyclical changes in the Earth's temperature, seen in Figure 12.16, and the corresponding advances and retreats of glaciers during the Pleistocene epoch. As such, the Milankovitch cycles must also be responsible for changes in CO_2(g), and CH_4(g), which are correlated with changes in temperature. Increases in temperature decrease the solubility of CO_2(g) in seawater, increasing the atmospheric loading of CO_2(g). Changes in temperature also change vertical mixing rates of ocean water, nutrient uptake rates by phytoplankton, and rates of erosion of continental shelves (which affect biomass loadings), thereby affecting mixing ratios of CO_2(g) (e.g., Crowley and North, 1999). Changes in microbiological activity resulting from changes in temperature may explain the correlation between temperatures and CH_4(g).

Figure 12.16 shows that a temperature minimum occurred about 150,000 y.a. Near that time, glaciers extended down to Wisconsin in the United States, and possibly further south in Europe (Kukla, 1977). Temperatures increased about 130,000 y.a., causing deglaciation. Over the Antarctic, temperatures rose 2 to 3°C above what they are today (Fig. 12.16). As the eccentricity of the Earth's orbit increased, temperatures cooled again, causing a renewed period of glaciation. During this period (the last glacial period), two major stages of glaciation occurred, the first starting 115,000 y.a. and the second starting 75,000 y.a. The second stage continued until about 6,000 years ago.

12.3.2.5. From 20,000 to 9,000 Years Ago

The last glacial maximum (**last ice age**) occurred 22,000 to 14,000 y.a. (Fig. 12.16). Depending on whether glaciation over eastern North America, western Europe, or the Alps is considered, this maximum is called the **Wisconsin**, **Weichselian**, or **Würm**. During the maximum, an ice sheet called the **Laurentide Ice Sheet** covered North America, and another called the **Fennoscandian Ice Sheet** covered much of Northern Europe. These ice sheets were about 3,500 to 4,000 m thick and drew up enough ocean water to decrease the sea level by about 120 m (CLIMAP, 1981; Fairbanks, 1989). The decrease in sea level was sufficient to expose land connecting Siberia to Alaska, creating the **Bering land bridge**. This land bridge allowed humans to migrate from Asia to North America and, ultimately, to Central and South America. The Laurentide sheet extended from the Rocky Mountains in the west to the Atlantic Ocean in the east, but only as far south as the Missouri and Ohio Valleys.

Temperatures during the last ice age were about 4°C less than they are today over the Northern Hemisphere and 8°C less than they are today over the Antarctic (Fig. 12.19). During the last ice age, Antarctic ice coverage expanded as did Arctic sea ice coverage. In the tropics, precipitation decreased, resulting in lower inland lake and river levels. Globally, near-surface winds may have been 20 to 50 percent higher than those today. CO_2(g) mixing ratios were about 200 ppmv, as seen in Fig. 12.16, almost half their current value. CH_4(g) mixing ratios were about 0.35 ppmv, 20 percent of their current value.

Figure 12.19 shows temperature change estimates in the Northern Hemisphere and from the Vostok ice core in the Antarctic during the last 20,000 years. The ice core data indicate that temperatures over the Antarctic increased between 17,000 and 11,000 y.a., with a hiatus between 13,500 and 12,000 y.a. The increases in temperatures were caused by Milankovitch cycle variations and were responsible for the melting of ice over the Antarctic starting 16,000 to 17,000 y.a. (Labeyrie et al., 1986; Jones and Keigwin, 1988).

In the Northern Hemisphere, temperature increases and deglaciation started around the same time as they did over the Antarctic, near 17,000 y.a. At first, Northern Hemisphere deglaciation was slow. From 13,000 to 12,000 y.a., an abrupt increase in temperatures hastened deglaciation. Around 12,000 y.a., temperatures dropped slightly, then plunged 10,900 y.a. This strong cooling, which lasted until 10,100 y.a., is called the **Younger Dryas period**. Dryas is the name of an Arctic flower. The Younger Dryas cooling period followed a shorter Older Dryas cooling period, which occurred