The Weston-Smith Physical Sciences Prize 2017-18

Question 1

How can we reconstruct the past climate of the Earth?

There is immense pressure on scientists to project future climate changes and to forecast the impact that these may have on the natural environment; this is a formidable task since the Earth's climate is so complex that it makes accurate predictions incredibly difficult. However, scientists have the ability to model and calculate climate change using evidence that is millions of years old and to analyse how it will have affected the natural environment. To uncover the causes of major events in the Earth's history as well as the origins of ecosystems, it is often essential to delve into that period's climate and identify not only the obvious deviations but also small nuances that may lead to a change in the environment as well as identifying how this may affect the behaviour and functioning of organisms. Therefore, it is important for scientists to be able to collect historical data and learn how to interpret the evidence. By cross-referencing data, scientists can more accurately predict how the climate will change in the future and the consequences it will have.

The Serbian geophysicist and astronomer, Milutin Milanković, believed that variations in solar radiation and orbital forcing were strongly responsible for the Earth's cyclical climate patterns which became known as the Milankovitch cycles.[1] One cause of these variations is said to be that the Earth has an elliptical orbit and as a result it undergoes apsidal precession (where the orbits rotate overtime). Likewise, another proposed effector is the axial tilt, varying between 22.1 and 24.5 degrees; the greater the tilt, the larger the variation of amplitude of insolation between seasons. Lastly, the eccentricity of the Earth varies too due to the gravitational attraction between Earth itself with Jupiter and Saturn. There is an increase in seasonal changes when the semi-minor axis shortens because the shortening increases the eccentricity resulting in larger variations in the distance between the Earth and the Sun, since the semi-major axis remains constant. The eccentricity of an ellipse can be defined in this way:

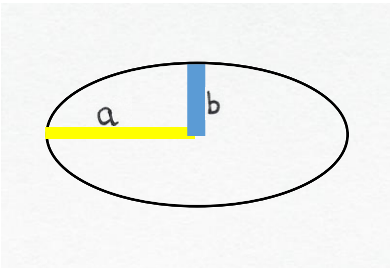

Figure 1: The semi-major (a) and semi-minor axis (b) of an ellipse

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

where *e* represents the eccentricity, *b* the semi-minor axis and *a* the semi-major axis. However there are now other methods of data analysis being used to expose the Earth's past climate; although much of the data is consistent with Milanković 's hypothesis, particular observations have begun to question it's validity as the hypothesis alone cannot explain all of the found anomalies.

Written records such as newspapers, diaries and logs contain historical data which can yield both qualitative and quantitative information about historical climate conditions. Despite reports dating back over hundreds of years, their sequence is rarely completed, anthropogenic causes such as urbanization may have disrupted the collection of data and, in the majority of regions, nothing was ever recorded; consequently, it would be unreasonable to solely rely on such human manufactured evidence. Consequently, although conventional historians tend to search for evidence in forms composed by humans, in a quest to reconstruct the Earth's past climate relying solely on these primary sources is not viable. Therefore, it is essential to build up further qualitative and quantitative evidence to support data

[1] An idea included in Milankovitch's hypothesis stating that the effect of a slow tilt of the Earth's axis and its orbital shape has an effect on its climate. The 'forcing' denotes physical events that influence the climate.

and unveil climates well-before the likes of human records; as a result, scientists have developed a series of proxy data.[2]

Paleoclimatology is conducted by retrieving proxy evidence from a variety of natural sources: ice cores, fossil pollen, lake sediments, ocean sediment cores, loess, glaciers, speleothems, tree ring widths and boreholes. However, before scientists may form conclusions from the proxy, it is essential that there is proof that it responds to environmental changes and this correlation is able to be measured from some record of events. Although this data is useful, it is necessary to consider that all organisms are known as 'biased reporters' because the gathered data is dependent on the conditions which the organism needs to grow and develop.

As previously explored, Vostok, the location of the first deep ice cores, provided evidence for the role of orbital forcing which features in Milanković 's hypothesis. However, the gaseous composition of the early atmosphere can also be predicted from the ice cores. All experiments performed on the ice must be undertaken in 'clean room' conditions because the readings are so miniscule it is essential for the measurements to be precise.[3] By using analytic techniques, scientists can identify the gases that were present by crushing the ice in a vacuumed hood (to ensure that no present atmospheric air was contaminating the sample) which releases the gases inside the ice which, subsequently, are then collected in a vial. Moreover, pollution, aerosols, radioactivity and metals can also be tested for through a variety of methods including mass spectrometry, gas chromatography and scanning electron microscopy. Ice cores can be dated by counting their bands because the variation in snowfall density results in variations of colour intensity. Alternatively, electrical conductivity can be recorded as it varies due to the differences of acidity in the summer and winter snowfall. Furthermore, isotopic identification can be useful in the dating of ice as it is also provides clues about the temperature of the atmosphere at that particular time. Oxygen isotopes are important in ice core analysis because oxygen-16 (accounting for 99.8% of oxygen atoms) and oxygen-18 (accounting for 0.2% of oxygen atoms) behave chemically identically and this, therefore, means that some water molecules will contain oxygen-16 whilst others will have oxygen-18. This is of particular interest because the water molecules with oxygen-16 will evaporate at a higher rate due to its comparatively low molecular mass. Ice is formed through layers of snow being compressed. In warm conditions, more oxygen-18 water molecules will evaporate from the sea than at lower temperatures so when precipitation occurs this difference is maintained in the snow and, hence, the ice that is formed. As a result, scientists expect more oxygen-18 present in the ice cores during warmer periods.

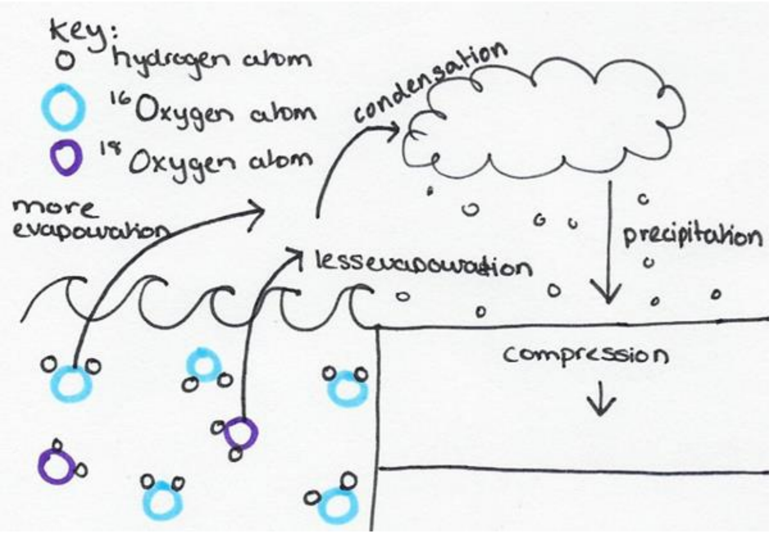

Figure 2: Diagram showing formation of oxygen-isotope abundances in ice cores.

Moreover, past surface temperatures can be identified through the examination of boreholes. This is due to the temperature changes at the Earth's surface propagating downwards into the crust and imparting thermal markings on the rocks below; consequently, this method may yield a historic representation of past surface temperatures dating back over the past few centuries but the ability to resolve details

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[2] Proxies are data that paleoclimatologists collect from natural resources.

[3] 'Clean room' conditions involve bodysuits, multiple layers of gloves for the scientists then ultraclean filters and vents to ensure no contamination of the air.

accurately decreases with time and, furthermore, the local anthropogenic alterations of the temperature must be evaluated to get a more accurate representation of the climate change. It is thought that the subsurface transient temperature perturbations are correlated to the one-dimensional heat diffusion equation:[4]

$$\frac{\alpha^2 \Delta T(z,t)}{\alpha z^2} = \frac{1}{\alpha}\frac{\alpha T}{\alpha t}$$

where z represents the depth and α is the thermal diffusivity of the Earth medium (of which the values may be located on a published data sheet). Due to heat transfer through the ground being slow, it enables scientists to produce a series of non-unique values of surface temperature, by adjusting the initial value regarding the effect of rising heat under the ground, using the mathematical inversion formula.[5]

Carlsbad Cavern is famous for its intricate rock formations. However, these caves also hold the otherwise unknown rainfall record for the south-west United States. Geologists refer to mineral formations found in caves as speleothems which include the likes of the stalagmite, stalactite, pillar and calcite curtain. Due to the rocks' secluded position, they are shielded from weathering and erosion taking place on the Earth's surface; consequently, the records preserved within the Earth's crust are thought to contain more information. In the atmosphere, the water vapour reacts with carbon dioxide to form weak carboxylic acid – otherwise known as acid rain. Precipitation occurs and the water hits the ground and, in the rocks which are permeable or porous, flows though the rocks picking up minerals such as calcium carbonate (which is found in the abundant permeable sedimentary rock limestone). However, when the water experiences a change of pressure and temperature, for example in a cavern, it will deposit a calcite crystal which builds up overtime, obviously dependent on amount of rainfall and carbon dioxide concentrations in the atmosphere.

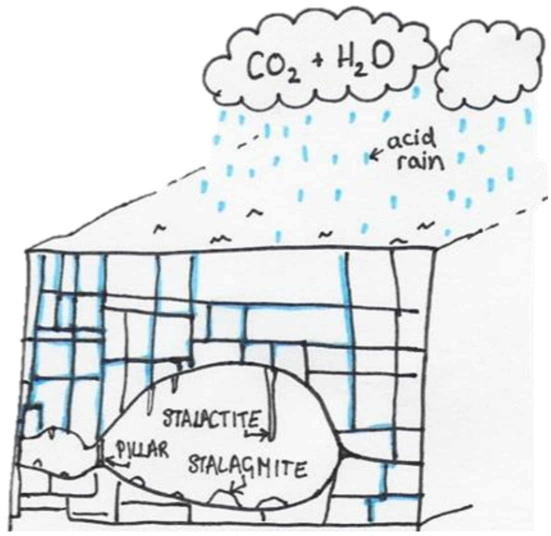

Figure 3: Diagram showing formation of speleothems in a limestone cavern.

On a different theme, loess, wind-blown dust, begin to provide extensive examples of past climate changes and help to explain how processes shaped the landscape; loess covers ten percent of the continents and is another crucial proxy in the quest to understand past climates. Layers of dust that have accumulated overtime can be analysed by scientists to provide suggestions regarding the historic winds and surface processes. Research methods such as luminescence dating have been used to understand the rate and timing of loess deposition; because certain minerals store energy from the sun at a known rate, by exposing a section from within the loess mass to heat or light, the energy released by the substance can be measured and compared to how much *should* have been released using given data values. Additionally, researchers are uncovering the predominant emitting areas using methods of single grain geochemical, mineralogical and magnetic methods on single dust particles of a range of sizes to find out about past climate change.

Since pollen is extremely resilient and resistant to decay and since each specie has different morphological characteristics, it provides information regarding the vegetation variation in an area over a particular time period. However, due to the relative pollen abundances from species being

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[4]The one-dimensional heat diffusion equation was put forward by Carslaw and Jaeger in 1959.

[5] They are a non-unique series because for each borehole temperature there are more than one possible surface temperature.

unequal, making predictions about population sizes (by making them directly comparable to the pollen distribution) inaccurate. Additionally, it is wise to be cautious about the deposition of pollen in water because non-climatic factors such as differential setting and turbulence may cause disparities among the pollen type and quantities. Consequently, fossil pollen must be used in a qualitative way in paleoclimatology; however, occasionally, fossil pollen may be used qualitatively providing there is evidence of a specie that only inhabits a niche environment.

Another botanical proxy is tree ring data. Trees are sensitive to local conditions, examples include intensity of sunlight as well as water availability. Andrew Douglass, a professor of astronomy and physics at the University of Arizona, discovered that characteristic sequences of ring widths in a region can indicate how the climate may have been changing: whilst wide rings show warm days with lots of moisture, narrow rings imply short growing seasons or an extreme lack of water. Furthermore, the ring colours indicate whether it was growing in the summer or winter; therefore, two rings of alternating colours express a year indicating the climatic conditions during that timeframe.

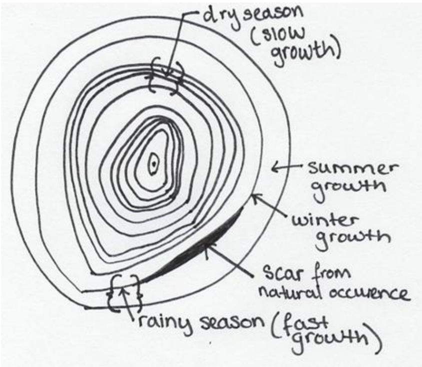

Figure 4: The colour and width of tree rings can provide an idea of historical climate conditions.

Similar to tree rings, corals also contain a form of banding but, unlike trees, this is due to chemical secretion. Coral reefs form when coral larvae attach themselves to submerged rocks. The coral polyps secrete calcium carbonate underneath their living cells; however, when it grows too large it shuts off a layer beneath them then continues to secrete in order that they remain living on the outermost layer. Since each polyp grows slowly (from 12.7 mm to 76.2 mm per year) and can live for centuries, and since it is highly sensitive to environmental factors which help it grow such as warm temperatures and shallow water to support their algal symbionts, it provides an excellent gauge concerning local climate change. The texture of the calcite that the polyps secrete varies seasonally giving a characteristic band-structure which allows scientists to yield data about the growing conditions during that year. Similar to that of ice cores, by looking at the oxygen isotope abundances it can provide evidence of the temperature of the water; however, its salinity can alter the equilibrium.

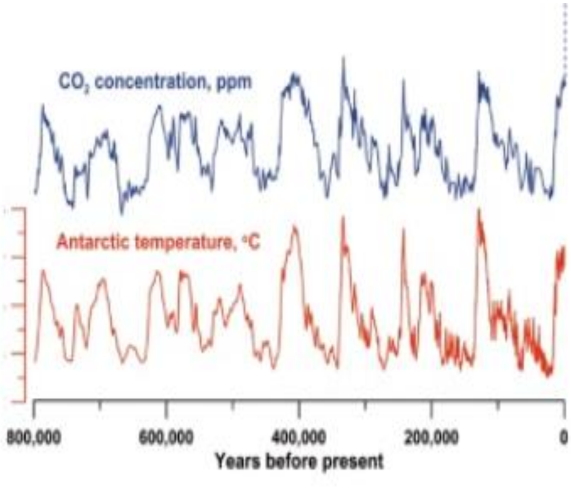

Figure 5: Graph showing changes of carbon dioxide and temperature during ice-age cycles in the recent geological timeframe. Source: Figure by Jeremy Shakun, data from Lüthi et al., 2008 and Jouzel et al., 2007.

Some people argue that, since the climate has constantly been in a state of flux, there is no necessity to address the present changing climate. In recent geological history, major climate change is based around the ice-age cycles which last about 100,000 years; it is this that people debate against the notion of harmful climate change. And this argument may have been more widely pondered upon if data had not revealed that today's warming is, in fact, ten times quicker than that at the end of the last ice-age; this is the fastest sustained natural change ever recorded.[6] Major past climate changes have resulted in extinctions (the five mass extinction events), migrations and dramatic changes on land and at sea; therefore, current climate activity should be a cause of concern because it is leaving little time for the environment and organisms to adapt.

[6] According to the www.royalsociety.org .

Indeed we may have many methods to reconstruct the past climate of the Earth but what is the importance of these discoveries? The conclusions that scientists draw from their evidence is likely to have an impact on civilisation worldwide in the near future. For example, the data gathered from ice cores may reveal the extent of the melting of polar icecaps during periods where the temperature was the same as that predicted in the next one-hundred years. Therefore, countries can prepare coastal defence mechanisms and migrate citizens to a less threatened position. Moreover, comparisons between forecasted climate changes and the impacts of similar past climates are important in management of global resources to ensure better preparation for what is to come.

2365 words

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