NASA Climate Change Education Program

Module One: Suggested Answers

Exercise One: The Phanerozoic Record of Global Sea-Level Change

The Data (Diagram One)

1. These data are an estimate of how sea level has changed over geological time
2. Change is sea level is measured relative to the present day and can be estimated using seismic stratigraphy and backstripping techniques widely used in the oil industry
3. The data cover the last 170 million years of geological time, from the Jurassic Period to the present day

Curve Characteristics

1. The frequency is highest over the last 10 million years. This is largely due to the impact of ice sheet growth and decay, but could also be a function of data resolution. The compaction of sediments, disconformities and diagenesis can make the detailed interpretation of older sediments more difficult
2. The curve is least variable prior to 100 million years during the early Cretaceous Period and Jurassic Period.
3. Sea level was primarily controlled by the rate of seafloor spreading during most of this time, and this is a much slower process than the geologically rapid dynamics of ice sheet growth and decay

Trends

1. The general trend between 170 mya and 55 mya is of rising sea level.
2. During the Upper Cretaceous Epoch sea level was nearly 150m higher than today as large submarine mountain chains along active spreading ridges displaced water onto the continental shelves

Cycles

1. A number of cycles over the period from 100 mya to 55 mya start with a rapid rise in sea level followed by a prolonged gradual fall and then a more rapid fall.
2. Each cycle is at least 2-4 million years long, much longer than expected from changes in ice volume. The cycles probably represent times when pulses of more rapid seafloor spreading caused the mid oceanic ridges to expand in volume, and then slowly subside as the lithosphere cooled and the ocean ridges reduced in volume. There is some suggestion that ice sheets did form on Antarctica during the Upper Cretaceous, and from this data you could hypothesis that the rapid fall in sea level that characterizes the termination of each of these cycles occurred as ice sheets formed in response to a combination of increased erosion (the drawdown of CO_2), and an increase in

albedo with falling sea level. Much more detailed analysis is required to resolve this question

Maximum Sea Level

1. The maximum sea level indicated from this record occurs between 52 and 54 mya, during the Paleogene (Lower Tertiary) Period. This sharp peak does not appear in other interpretations that indicate a maximum during the Late Cretaceous
2. It is tempting to link this spike in sea level to the Paleocene Eocene Thermal Anomaly (maximum), but the age does not fit. The PETA occurred around 55 mya, and the maximum on this record it recorded between 52 and 54 mya. The most likely cause of this sudden rise is a further pulse in seafloor spreading, perhaps associated with the opening of the North Atlantic Ocean
3. Following this maximum during the Paleogene, sea level started to fall. At first this was probably once more due to the impact of global tectonics, but later the impact of ice sheet development became increasingly important

Exercise One: Estimated Global Sea Level

The Data (Diagram Two)

1. This diagram covers the last 6 million years
2. Sea level varied relatively little from 6 mya until 3.4 mya, staying mostly within 20 meters both above and below current levels. From 2 mya to 1 mya sea level fell and from 1 mya to the present oscillated between levels higher and much lower than today

Amplitude

1. Between 8 mya and 6.2 mya sea level changed by as little as 20m above and below current levels
2. Between 6.2 mya and 3.4 mya sea level varied by as much as 50m both above and below current levels
3. Between 3.4 mya and today, the amplitude of these swings in sea level intensified. Maximum sea level does not change much, staying within 20m above current levels, but minimum sea level plunged to more than 120m below current levels
4. These changes in amplitude reflect the development of ice sheets as more water was trapped near the poles in both hemispheres

Exercise One: Estimated Global Sea Level II

Interpretation (Diagram Three)

1. This graph covers the period from 2 mya to the present
2. Around 1 mya the frequency of the sea level record “flips” from ~42,000 years on average to ~100,000 years on average. It is not clear why the cycles

changed, or if they will “flip” back again in the future. This certainly appears to be due to Milankovitch cyclicity, but the 42,000 year signal is much stronger than the 100,000 year signal, so it is not at all clear why this should start to dominate the climate cycle

3. The amplitude of the record has increased significantly over the last 1 my Most of this change reflects periods when sea level was much lower than today’s
4. These oscillations correlate with Milankovitch obliquity (tilt) and eccentricity cycles
5. These changes reflect the onset of full glaciation in both hemispheres
6. Unusually low sea level occurs during glacial maxima when most water is stored on land in massive ice sheets.

Exercise Two: Estimating Global Temperature

LR04 Benthic Stack

1. There data are oxygen isotope concentrations
2. The data are created from the analysis of the tests (shells) of benthic (bottom dwelling) marine foraminifera recovered from marine cores. Many cores were collected to contribute to these data, and the data were superimposed (stacked) together. This helps to reinforce important but weaker signals and reduce the amount of background random “noise”
3. The data cover the last 5 million years
4. The Y-Axis is a measure of the oxygen isotope ratio, and can be related to ocean floor temperature
5. The estimate of sea floor temperature between 6 mya and 3.4 mya is fairly constant
6. From 3.4 mya to the present, changes in the oxygen isotope composition of benthic foraminifera (and thus temperature) parallel changes in sea level and both a linked to the growth and decay of polar ice

LR04 Benthic Stack (II)

1. This is an enlarged section from the same data covering a period from 2 mya to the present day
2. The range in amplitude of this record parallels calculated changes in sea level
3. Sea level fell globally as the climate cooled and more ice was locked up at the poles. These changes are naturally reflected by colder bottom water in the deep ocean
4. These changes are also be controlled by Milankovitch obliquity and eccentricity cycles
5. The minima on the Y-axis deepen during the period from 1 mya to the present
6. This reflects colder ocean floor temperatures

7. Colder ocean floor temperatures allow more of the Oxygen 18 isotope to enter into the tests of the benthic foraminifera

Exercise Three: The NGRIP Greenland Ice Core

The Data

1. These data are oxygen isotope ratios measured from the NGRIP Ice Core, and can be related to the temperature of the atmosphere when the ice first formed (probably as snow)
2. As temperatures fall, the level of the Oxygen 18 Isotope in ice falls (note: this is the opposite trend from that observed in the shells of foraminifera)

Pattern

1. The overall pattern is very cyclical
2. Rapid climate change was very common during this period
3. A rapid rise in temperature is most often followed by a period of much slower temperature decline
4. There is evidence of at least 20 significant climate cycles over the last 80,000 years
5. The difference between the maximum value of $\delta^{18}O$ at -34 ‰ and the lowest at -46 ‰ is around 12‰. Using the graph, this translates to a temperature difference of around 17°C given a relationship ~0.7°C per mille of $\delta^{18}O$.

Temperature

1. The temperature change represented by the Dansgaard Oeschger Cycles (D-O cycles) over the interval 5,000 to 3,000 years ago is in the order of 8°C (6‰)

The Last Glacial Termination

1. The temperature range over the interval 12,000 to 10,000 years ago is in the range of 12°C (8‰). This marked the termination of the most recent glacial period
2. The average rate of change over the interval 12,000 to 10,000 years ago was 12°C over a period of 2,000 years or 0.6 °C per century
3. This compares to a modern global rate of change around 0.7°C per century on average. Temperatures are now rising as fast globally as they were in Greenland during the last glacial termination

Cycle Length and Origins

1. The cycles vary in length from over 2,000 years (ca 76,000 ya) to less than a thousand years (ca 27,000 ya)
2. There is no clear and consistent pattern to the D-O cycles that can be determined from these data
3. There is no clear correlation with the period of any known Milankovitch cycle

Exercise Four: The GISP Greenland Ice Core

The Data

1. These data from the GISP ice core extend back 30,000 years. This period covers the termination phase of the last major glacial period
2. The Y-Axis measures temperature derived (as in the previous exercise) from Oxygen isotope data
3. You should be able to identify around 13 D-O cycles during this period (marked by arrows)
4. These data agree closely with the NGRIP data
5. These data suggest that during the Bølling-Allerød event the temperature increased from -45°C to -32°C in around 500 years giving an average rate of 2.6 degrees per century
6. The time from the peak of the Bølling-Allerød event to depths of the Younger Dryas event was around 1,866 years and the temperature dropped from -32°C to -50°C at an average rate of 0.96°C per century.

Exercise Four Graph Two: The GISP Greenland Ice Core

Rates of Change

1. The average rate of warming indicated by these data over the interval from 11,000 to 10,000 years ago is around 0.5°C per decade
2. The maximum rate of warming indicated by these data over the interval between 11,600 and 12,000 years ago is around 4.6°C per century!
3. The maximum rate of cooling during the interval 14,500 to 12,700 years ago is 0.97°C per century. This temperature anomaly occurred at the same time glacial Lake Agassiz partially emptied into the North Atlantic and interrupted the flow of the North Atlantic thermohaline current

Exercise Four Graphs Three and Four: The GISP Greenland Ice Core

Rapid Climate Change

1. The data indicate that rapid changes in temperature are common over this period, but the rate of warming is almost always higher, often twice as high as the rate of cooling
2. The maximum rate of temperature change observed occurred around 14,688 years ago at over 11°C per century and the maximum rate of cooling occurred around 12,973 years ago at over 8°C per century

Climate Stability

1. The climate over the last 11,000 years had been unusually stable
2. This is in marked contrast to a high level of climate instability towards the end of the last glacial period when there were very large swings in climate

3. Interglacial periods in general are times of much more stable climate, although past interglacial periods have been interrupted by periods of more rapid climate change
4. Glacial periods cover a much longer period of time, and are characterized by cyclical changes in climate that are accompanied by rapid changes in climate at the start of each cycle and often by rapid cooling at the end of each cycle
5. The end of the last main glacial phase and the transition into the present interglacial phase was characterized by very rapid changes in a very unstable climate

Exercise Five: Greenland Ice Cores

The Data

1. These data are Oxygen Isotope analyses from the GRIP, DYE 3 and NGRIP Ice Cores. They span the same period of time from the end of the last glaciation to the present day
2. The data agree closely over this period

The 8,200 Year Anomaly

1. The Younger Dryas event is not fully visible in any of the three data sets as it occurred approximately between 12,800 and 11,500 years ago
2. Between 8,000 and 8,300 years ago there was a sudden fall in temperature
3. This 8,200 year temperature anomaly occurs at the same time glacial Lake Agassiz partially emptied into the North Atlantic and interrupted the flow of the thermohaline current
4. This was a much smaller event than the Younger Dryas. The 8,200 year event also occurred when Lake Agassiz released a further flood of fresh water into the North Atlantic that also interrupted the flow of the thermohaline current

General Trend

1. Following a temperature maximum around 8,000 years ago, the temperature in Greenland declined steadily by around 3°C at a rate of -0.038 °C per century. This is reflected in changing Oxygen Isotope values in the ice cores from around -33.5‰ to -35.5‰
2. The climate of Greenland is strongly affected by the strength of the thermohaline current, and by the path of the polar jet stream. The record of climate change in Greenland is very likely to reflect the general trend of climate change in the Northern Hemisphere, and in many ways actually determines the path of climate change in the Northern Hemisphere
3. Climate change in Greenland is much less likely to have an immediate impact on global climate (see exercise 6)

Exercise Six: The GISP Greenland Ice Core and Byrd Antarctic Ice Core

The Data

1. These are Oxygen Isotope data
2. The data *(here and here)* are extracted from ice cores in Greenland and Antarctica. They span a period from 10,000 years ago until 90,000 years ago towards the end of the last major glaciation and allow comparison of climate change in the Northern and Southern Hemispheres

Compare the records of Greenland and Antarctica

1. There is close agreement between the two records in many places such as the interval between 7,400 and 8,500 years ago. This reflects the overall impact of the Milankovitch cycles that affect global climate
2. There are a number of intervals (how many can you find?) when the temperature in the Antarctic ice core rises as the temperature in the Greenland ice core falls. Look at 21,000 to 24,000 years ago and 55,000 to 57,000 years ago and 64,500 as examples. You should be able to find many more examples
3. Between 70,000 and 40,000 years ago there are some periods when there is a close parallel relationship between temperature at both locations, and others where temperatures change in parallel but in an opposite sense. There are also some periods such as 6,200 years ago when there was a sudden rise in temperature in Greenland with no apparent impact on Antarctica
4. These intervals normally last for between a few hundred years and may be related to changes in the strength and path of the thermohaline current that determines the hoe much warm tropical water flows to both the north and south polar regions

Termination of the last glaciation

1. The data from these cores suggest that some warming may have started to occur in Antarctica prior to Greenland (the interval 23,000-22,000 years ago)
2. Warming in Antarctica was well under way by 21,000 years ago and was much more constant and sustained than in Greenland
3. The Younger Dryas event is clearly visible in the Greenland data at 12,500 years ago
4. Neither the Younger Dryas event nor the Bølling-Allerød event are apparent in the Antarctic core data
5. Global radiative forcing was the primary factor that drove warming in Antarctica. Warming in Greenland was modulated by the impact of glacial melt water on the strength and flow of the thermohaline current

Exercise Seven: The Vostok Antarctic Ice Core

The Data

1. These data are values of temperature and carbon dioxide derived from the Vostok Ice Core. Temperature is determined from oxygen isotope data and carbon dioxide from the direct analysis of atmospheric gases trapped in the ice
2. They span a time range from 422,000 years ago to the present day

Glacial Cycles

1. There are four complete glacial cycles and five (incomplete) interglacial cycles represented in these data
2. The present interglacial cycle has lasted longer than any of the previous four interglacial periods, a function of the 400,000-year Milankovitch cycle

The Temperature Record vs. CO_2

1. The CO_2 record broadly follows the temperature record, but the data show that the detailed relationship is varied and complex. Using data from this exercise, you can create a plot CO_2 against temperature and test the degree of correlation. You should discover a value of R^2 around 0.75. This is an impressive level of correlation, but as much as 25% of the variation still appears to be due to other factors such as changes in ocean circulation, and feedback within the carbon cycle
2. Temperature tends to fall faster
3. Temperature tends to increase faster
4. Global temperature is naturally controlled by changes in external radiative forcing that are modulated and amplified within the Earth's climate system. Carbon dioxide is one of the most important natural agents in this process. The release of CO_2 from the oceans as they warm, and its capture and storage by the oceans as they cool, is one of the most significant factors driving climate change, but it is not the only factor involved. These data clearly show that to understand the relationship between global temperature and CO_2 it is also important to consider how interaction between the atmosphere, hydrosphere, biosphere, cryosphere and lithosphere all exert an important control on climate

Exercise Eight: The EPICA Antarctic Ice Core

1. These data combine information from a number of sources to help interpret the EPICA Ice Core
   a. The data on Milankovitch cycles are derived from astronomical observations

    b. The data from the EPICA ice core are temperature derived from oxygen isotopes, and the level of carbon dioxide measured from gas trapped in the ice cores
    c. The data on global sea level is the same as used in the first exercise
2. The data span the previous 800,000 years of Earth history
3. You should be able to identify 8 major glacial and interglacial cycles lasting around 100,000 years. The cycles prior to 500,000 years are more complex with more pronounced stadial and interstadial periods
4. These data extend the record for twice as long as the Vostok core. The best match to the configuration of the Milankovitch cycles today was around 400,000 years ago and this period was associated with a particularly long interglacial period that lasted up to 30,000 years in contract to the 20-30,000 period of most other cycles

EPICA Temperature and CO_2

1. The temperature starts to increase some time after solar isolation increases in the Northern Hemisphere.
2. It takes time for global temperature to respond to relatively small changes in external radiative forcing, and for these to be amplified within the Earth climate system. This gap between the onset of forcing and the onset of warming/cooling is know as the lag time
3. As with the Vostok ice core, there is a close relationship between temperature and CO_2. Plot these data against each other and test this correlation. You should get an answer around 0.75, but notice that the data suggest that the relationship is not entirely linear. Temperature appears to increases much more slowly at higher levels of CO_2. Can you think of any reasons for this? Two possible factors are the rapid growth of vegetation in the Northern Hemisphere following deglaciation, and the saturation of parts of the infrared spectrum most affected by CO_2
4. You may want to use the original data to “zoom in” on some period of interest as this can be difficult to see on the scale of this chart, but as with the Vostok data there are examples of temperature rising before CO_2 with a lag time of anything up to 1,000 years

EPICA: Dust in the ice cores

1. Most of the dust in ice cores comes from the wind erosion of exposed glacial terrain and from volcanic activity. Very small amounts of dust can be of extraterrestrial origin
2. There is most dust in the ice core record when temperature is close to a minimum, sea level is at its lowest, and ice sheets are most extensive or just starting to retreat
3. When the temperature is at a minimum the ice sheets are most extensive, sea level is lowest and a large part of the continental shelf is exposed to wind erosion. In addition, and especially when the ice sheets start to retreat, there

are extensive areas of glacial outwash and moraine that are subject to intense erosion by the wind

Exercise Nine: The future?

1. There is no “correct” answer to this, but students can use this graph to look at the general relationships between orbital cycles and temperature and make an educated guess. Based on the response of the Earth climate system to Milankovitch radiative forcing over the previous 800,000 years, it seems probable that we can expect a further repeated cycle of glaciation and deglaciation every 100,000 years for at least the next 800,000 years. Only planned anthropogenic intervention or the slow movement of the continents will change this in the foreseeable future