TRACKING GLOBAL CLIMATE CHANGE: MICROFOSSIL RECORD OF THE PLANETARY HEAT PUMP

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INTRODUCTION

THE OBJECTIVE of this exercise set is to integrate knowledge from several scientific disciplines and learn something interesting about the way the world works. I want to use some basic principles from physics, biology and geology to see how a large scale planetary process, the transport of heat over the earth's surface, operates and has operated over time. This topic is of basic scientific interest, and it has real importance to the growing societal interest in global climate change. This applies whether natural variation in climate or human induced change are under discussion. The set of exercises that follows will examine how energy is absorbed by the earth from the sun; how and why this energy is distributed over the earth's surface; what controls energy distribution; how we can track the energy distributing process using the oceanic microfossil record; and what that record shows us about variation of heat distribution with time. This is an exercise in global climate change because the climate system is driven by the heat distribution process.

Target Group: Grades 8-16

Teaching Approach: The approach taken here is an interactive one where questions are asked and simple experiments are suggested to find answers to those questions. Along the way the principles of various sciences are used, so this will be cross- disciplinary and integrative. I prefer learning by doing and shall approach my topic from that point of view.

MATERIALS NEEDED

1) Seven diagrams included in this article
2) A heat source, e.g., stove top or bunsen burner
3) A pot and a lid (not a latch on type) with a fitting for a thermometer. You can make your own with any pot and lid by making a hole in the lid just big enough for the thermometer and fitting the thermometer with a ring, or masking tape ring, to keep it in place.
4) A bar or rod of iron (nothing fancy needed here) and a heat resistant glove
5) A photometer, some device to measure light intensity, even a camera with a light

meter will do
6) A calculator
7) Samples of foraminifera (microfossils) provided by us, or from your own source
8) A regular binocular microscope

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UNDERSTANDING ENERGY DISTRIBUTION ON THE EARTH

Energy to make things happen — The laws of Physics tell us that nothing in nature happens without an input of energy. Climate happens because the earth's surface is supplied with heat. Some of this heat comes from the inferno inside the earth, but our planet would be pretty cold without the supply of energy we receive from the sun. The sun's energy comes to us as light. An experiment described below shows that light carries energy and that energy can be converted to heat.

Figure 1 shows the earth receiving heat from the sun. Thanks to the sun's light we have a continuous input of energy that warms us. But this raises an issue. If we have all this energy arriving at the earth, why don't we heat up until we melt? To prevent such a calamity, we have to lose energy as well as gain it. If the earth's temperature stays the same over time then we must lose energy at the same rate that we gain it. This is called a steady state (input=output). How does the earth lose energy? The same way we gain it, through radiation of light. This point is made in the experiment described below. As the earth is warmed by the sun, so it is cooled by radiating its own light into space. The difference is that the sun's incoming light is visible to us, but the light escaping the earth is at a wavelength below our range of detection — infrared. We feel this type of radiation (see below), but we can't see it.

RADIATION EXPERIMENT

It is possible to see the relationship between radiation and heat with a simple experiment using a bunsen burner (or other heat source) and a rod of iron. I learned this in shop class when I was in high school. Simply begin heating the iron over the flame. Remember to use your heat resistant glove. After a few moments ask the class what the temperature of the metal should be. Then ask someone to hold their hand relatively close to the metal and ask them what they feel. NOTE: SAFETY RULES HERE, prevent contact with the metal (a point made graphically by my high school shop teacher). We have in our skin, especially our hands, sensitivity to infrared (long wavelength) light. We can feel the heat of the metal at a distance, because it is radiating infrared light. So, as the metal warms in the flame it also cools by radiating energy. Ask the class how they can test for this radiation and be sure that what we are feeling isn't simply air warmed near the metal.

The final demonstration is to hold the metal in the flame until it starts glowing red. It has now reached a temperature hot enough so that it radiates in a wavelength we can see. If you look up the wavelength of red light and use the equation in Figure 1 you could calculate the temperature of the metal.

The Earth's temperature balancing act — The earth is a sphere and this has major effects on planetary heating due to incoming solar radiation. As Figure 2 shows, the incoming sunlight hits the earth directly only at low latitudes where the sun is directly overhead. At higher latitudes the sun is lower in the sky and the sunlight hits the earth's surface at an angle. This angle gets larger and larger as latitude increases, by the time you reach the poles the sunlight arrives at a considerable angle (the sun is low in the sky). This angle of radiation causes the sunlight to spread over an increasingly large area as you go from the equator to the pole. So, if you take your standard meter squared of the earth's surface, it gets a lot more energy as sunlight at the equator than it does at either pole. An experiment described below illustrates this point, as does Figure 2. The result is that the earth's surface is differentially heated, with the equator getting the lion's share of the incoming energy.

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By contrast, the earth radiates (loses) energy to space pretty evenly with much less dependence on latitude. The main controlling factor here is the temperature of the upper atmosphere (where the escaping radiation comes from). This temperature doesn't change enough to make a big difference in radiation loss as you go from the equator to the poles. Figure 2 shows a comparison of energy input versus energy loss on a line from the equator to the poles. It is obvious from the figure that there is net gain of energy at low latitude (radiation gain is greater than radiation loss) while there is net loss at mid to high latitudes. This is an interesting result and of profound importance to climate on earth. If this was all there was to the story then the low latitudes would heat intolerably and the poles would cool to temperatures that would make the present day arctic seem balmy by comparison. Luckily for us, there is more to the story.

ANGLE OF RADIATION EXPERIMENT

The amount of radiation we receive on the ground depends on the angle of the sun in the sky. This is very important to climate. A simple demonstration of the point can be made by setting up a photometer (can you find one of those old meters cameras used to need?) so that it is looking directly upwards. Then take a light (not too strong, don't blow its brains out) and get a meter reading when the light is directly overhead. Then, progressively increase the angle of the light to the vertical as it shines on the meter (keep the distance from light to meter constant). Record meter readings as you do this. You should find a relationship that is proportional to the sine of the angle (if horizontal is taken as zero degrees), with readings decreasing as the angle to the "horizon" goes down.

Spreading the wealth: Heating higher latitudes — Figure 2 shows a net heat gain at low latitudes and net loss at mid to higher latitudes. These gains and losses have to balance for the earth's surface to be tolerable. We have to transport heat from the low latitudes to the higher latitudes so as to heat them. This transport is what the overall movement of the atmosphere and the oceans is all about. In this exercise we are going to concentrate on the ocean's surface to develop the examples I will use. The reasons for this are several. On the whole, the atmosphere and the oceans transport about equal amount of energy from the equator to higher latitudes. However, atmosphere's behavior depends strongly on its underlying surface and that is primarily oceans (3/4 of the earth is ocean). Also, water holds heat much better than does air. See the experiment below. Because of this property, a three meter layer of the surface ocean (about 10 feet thick) can hold as much heat as the entire overlying atmosphere (roughly 10 km thick).

STORING HEAT EXPERIMENT: WATER VS. AIR

In this experiment we compare the time needed to heat a volume of air and a similar volume of water. Take a pot with a lid in which a thermometer is fixed so that it hangs down into the pot a little ways, but does not touch the bottom of the pot. SAFETY TIP: Don't use a mercury thermometer in case breakage occurs, and keep the thermometer away from flame and hot surfaces. Use the bunsen burner (or other heat source) to heat the pan and record both time and change in the internal air temperature of the pan. SAFETY TIP: don't let this go on too long or the thermometer will break from overheating. Now try the same experiment with water in the pan. Make sure the thermometer tip is in the water, and that you start with water at room temperature. The amount of heat needed (time in our experiment) to warm the water is much greater than is needed for air. Water has the higher thermal inertia, it takes longer to warm up, meaning it stores much more heat per degree of temperature change than does air, so it can carry much more energy from the equator to the poles per unit volume. Even though it stores much less energy, he atmosphere plays a role in heat transport because it carries its small load more quickly than the ocean (atmosphere transit times measured in weeks, ocean transit time measured in months).

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Heat on the move — Concentrating then on the oceans, Figure 3a shows the temperature of the ocean's surface. We will pay particular attention to the North Atlantic and notice that the temperatures are highest at low latitudes and cool northwards. However, there is an asymmetry. The western side of the ocean is warmer than the eastern side. This is because the movement of water in the Atlantic is dominated by a large circular feature, shown in Figure 3b, called the subtropical gyre. In this gyre, water moves northward on the western side. Warm water moves towards the pole in what is called a *western boundary current*. This current in the north Atlantic is the *Gulf Stream*. The Gulf Stream is like an enormous river flowing past watery banks. (Off New York City if you take a steamer headed to Europe, you will see the edge of the Gulf Stream clearly as a distinct zone where the cold greenish water of the Labrador current, closest to shore, gives way to the warm blue water of the Gulf Stream.) The Gulf Stream carries a tremendous amount of heat from the equator, up past the Carolinas and then across to northern Europe. At higher latitudes that heat is released to the cold air blowing over the ocean. This warm air gives northern Europe a moderate, rainy climate. Notice that on the western side of the Atlantic at about 50 degrees latitude we have Canada and Greenland with subpolar, cold, climates. At the same latitude on the eastern side of the Atlantic we have Ireland, Great Britain and lower Scandinavia all of which have mild climates. The difference is the Gulf Stream and the tremendous amounts of heat it transports northeastward to the higher latitude atmosphere.

USING MICROFOSSILS TO UNDERSTAND CLIMATE CHANGES IN THE PAST

Tracking the Gulf Stream high latitude heater — In looking at the Gulf Stream we have defined one of the major climatic factors on planet Earth. This factor has a large effect on Europe, Asia and the Arctic. Think about the effects of shifting the travel path of the Gulf Stream, either farther northward or deflected southward. You might wonder how variable this Gulf Stream system is over time. Does it change its position and characteristics very much? To answer this question we need something that has tracked the Gulf Stream and the north Atlantic subtropical gyre over time. As it happens, recorders of the surface ocean accumulate continuously on the seabed in the form of the skeletons of tiny creatures that lived in the surface currents. As these skeletons accumulate year by year on the seafloor, there builds up a continuous story of ocean behavior that we can read. If we can sample that skeleton pile at progressively deeper levels below the seabed we can look into the past. Then if we know how to interpret the skeletal remains in terms of surface ocean properties we can view Gulf Stream behavior through time.

How do we read the fossil record in terms of ocean properties? Among the remains collecting on the seafloor are the shells of tiny creatures called *foraminifera*. These are amoeba that happen to make intricate calcite skeletons and live their lives as *plankton* floating in the surface waters of the ocean and grazing on the microscopic plants that live there. The species of these *planktonic foraminifera* are adapted to particular oceanic environments. In particular, different species have different temperature requirements. So by looking at the species composition of the foraminiferal skeletons preserved in the seabed, we can interpret the temperature of the waters that flowed over our sampling location. We just need to learn to recognize a few different kinds of these foraminifera so that we can work with their abundance variations in the seabed sediment record and read the history of the north Atlantic climatic system.

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Telling foraminifera apart— In all, there are about 34 living planktonic foraminiferal species. We are using only seven species that are easy to recognize, are diagnostic for temperature, and are generally abundant in the oceans. Figure 4 describes the seven and explains how we identify them.

Planktonic foraminifera make their shells by sticking discrete chambers together in a growing spiral. Each chamber has an opening called the aperture and in some cases can have smaller, secondary openings usually on the side opposite to the main aperture. Since these chambers are connected together in increasing size into a spiral (like a snail shell in shape), we can define two sides to the foraminiferal shell. One side has the spiral on it and is called the *spiral side*. The other side, opposite to the spiral of chambers which gradually increase in size, is called the *umbilical side*. It is usually on the umbilical side that we can see the main opening (aperture) of the final and biggest chamber.

Generally speaking, planktonic foraminifera come in two forms. One has chambers that are inflated like balls and have a rough, crystalline texture. Some of us call these, affectionately, crispy critters. These globose types are called *Globigerina* (their genus name). There are several species that will be of use to us. The other major group of foraminifera are more disc shaped and not so inflated. Also, their texture is usually smoother and shiny looking. These are the *Globorotalia*. There is also one other group which can be confused with the *Globigerina* but have a different surface texture. These are the *Globoquadrina* and we will treat them only to recognize two important species.

Digging into the past— To use our foraminifera we need to know what the relationship is between species' abundance in ocean bottom sediments and surface ocean temperature. One way of determining this is to look at species' abundances in modern surface sediments and compare this to modern sea surface temperatures (SST). Figure 3 shows a map of modern average annual surface ocean temperatures for the Atlantic Ocean. Figure 5 shows species' abundances in surface sediments at the ocean bottom as a percent of all the planktonic foraminifera there. Comparing these two figures will show you the temperature responses of our species.

SPECIES TO TEMPERATURE PLOTS: AN EXERCISE

Make diagrams plotting species abundance in the sediments against the surface ocean temperature overlying the sediment locations. This can be a simple, general exercise or can be developed into a sophisticated one. To do the latter you can select locations on the temperature map and superimpose these (use tracing paper) on the species abundance maps to build a data table listing temperature against species abundances at each location. The data on this table can be plotted on axes of species percent vs. temperature.

Following the plotting, students can interpret species temperature requirements — e.g., how well does temperature control that species' percentage in the deep sea sediments? Students might consider other factors to which the foraminifera could respond that influence their abundance in the sediment record.

Keep the plots, you can use them in an exercise developed below.

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When the world was different: The last glacial age — Paleo- climate studies tell us that over the past several hundred thousand years the earth has experienced a number of *glacial epochs* when polar ice caps expanded and North America and northwestern Europe were covered by large glaciers and ice sheets. The cause of these large scale climate changes is mysterious, but here we can wonder: **What was the North Atlantic heat pump doing during glaciation?** How is it possible to build up huge ice sheets around the margins of the North Atlantic with the Gulf Stream hauling large quantities of heat poleward?

We can use our foraminifera to examine the last glacial interval, about 20,000 years ago, to see what the North Atlantic ocean was like at that time.

To do this we need to sample the ocean floor at a level that corresponds to the last glacial time period. This can be done using a device called a piston corer which shoves a metal barrel into the seafloor. The sediments in the barrel can be sampled and age dated (modern at the top of the barrel, getting progressively older down the core). If we do this at a number of locations in the ocean, we can find sediments of the age we want and develop a map view of ocean conditions for times in the past. Once we have the right samples, we examine them for their foraminiferal species percentages and then apply what we learned above to interpret the past.

EXERCISE: INTERPRETING FORAMINIFERAL PERCENTAGES

Table 1 lists foraminiferal species percentages for three samples taken from modern sediments. Use these and the species distribution maps (Figure 5) to determine where these samples came from geographically. Locate the spots in the North Atlantic where you would find species percentages such as those listed in the Table. You will find that only certain distinct regions of the ocean will give you the same percentages as each sample.

Once you have done this, use the surface ocean temperature map for the North Atlantic and determine what temperatures are represented by each sample. Doing this will "calibrate" your modern samples to temperature values. When we find older samples with similar species percentages in them, we can interpret the temperature of the ocean for times in the past. We make our interpretations based on a comparison of modern foraminiferal percentages to the percentages we find in older samples.

Table 1	PERCENT OF SPECIES		
SPECIES	SITE 1	SITE 2	SITE 3
pachyderma, left coiling	50	1	0
pachyderma, right coiling	8	14	0
inflata	0	30	0
bulloides	15	12	0
ruber	0	15	32
sacculifer	0	2	35

menardii	0	8	10
dutertrei	0	7	8

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EXERCISE: THE ATLANTIC DURING THE LAST GLACIAL EPOCH

Table 2 lists species percentages for glacial age samples collected at the spots shown on the map in Figure 6. Use the modern ocean species percentage maps (Figure 5) to figure out where these samples would be located geographically if they were modern. From this interpret the temperature represented by each of the glacial age samples. Use the North Atlantic temperature map (Figure 3) for this. If it all seems confusing, the sequence of steps here is as follows: (1) Use the modern ocean species percent maps (Figure 5) to determine what locations in the modern ocean would give you species percents like those in the glacial age samples. (2) Mark these modern ocean locations onto the modern ocean temperature map (Figure 3), and record the temperature range represented by the glacial age samples. (3) Return to the glacial age sample location map (Figure 6) and write down the temperature deduced for each sample location.

Now you can make an interpretation, plot in some *isotherms* (contour lines of equal temperature like those on the modern day temperature map) on your glacial age map. Compare your map for the glacial time period to the map for the modern North Atlantic and note the differences. What would you conclude about the subtropical gyre and the path of the Gulf Stream?

Table 2	PERCENT OF SPECIES					
SPECIES	SITE1	SITE2	SITE3	SITE4	SITE5	SITE6
pachy. left	92	1	0	90	1	0
pachy. right	3	15	4	6	16	5
inflata	0	14	11	0	15	7
bulloides	0	28	14	0	30	12
ruber	0	3	11	0	5	17
sacculifer	0	0	2	0	0	4
menardii	0	0	0	0	0	1
dutertrei	0	0	0	0	0	0

FOR THE TEACHER: SOME POINTS ABOUT CLIMATE CHANGE

The point of this series of exercises is that we can use a logical process to deduce the behavior of important parts of the climate system. In this case the micropaleontological record gives us the material to work with. What it shows us is that certain parts of the climate system can be very sensitive in their behavior. Figure 7 shows a reconstruction of the North Atlantic based on a sophisticated version of what we did above. It shows that temperatures in the North Atlantic changed drastically in the past. The Gulf Stream changed its travel path considerably as the subtropical gyre shrunk and shifted southward. The result was that the heat pump carried its load more eastward than northward It locked heat closer to the equator, which underwent little glacial age cooling. But this set up isolated the higher latitudes and deprived them of their heat supply. So, large sections of the northern continents cooled and froze. Huge ice sheets spread over the land (imagine an ice layer a mile thick, as modern interpretations suggest) and sufficient ice to drop sea-level by over 100 meters. If you work out the numbers with figures from your gazetteer, this is a tremendous amount of water, and a lot of ice.

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What we don't really understand is what triggers these "mood" swings in the global climate system. For now, we have good evidence that certain parts of the climate system, like the North Atlantic heat pump, are quite sensitive and can change dramatically in their behavior. The challenge now is to understand why.

SOME ADDITIONAL RESOURCES

The Oceans:
(1) Check the local university library for introductory oceanography texts. There are dozens of these available now and they are all pretty similar to one another.

The Foraminifera:
(1) Introduction to Marine Micropaleontology, by B.U. Haq and A. Boersma, Elsevier, 1978, ISBN 0-444-00267-7, library listing: QE719.I57;
(2) Oceanic Micropaleontology, edited by A.T.S. Ramsay, volume 1, Academic Press, 1977, ISBN: 0-12-577302-1

The Glacial Age World:
(1) The Surface of the Ice-Age Earth, by CLIMAP Project Members, in the journal Science, volume 191, pp. 1131-1137;
(2) North America and the Adjacent Oceans During the Last Deglaciation, edited by W.F. Ruddiman and H.E. Wright, 1987, The Geology of North America, volume K-3, published by the Geological Society of America, ISBN: 0-8137-5203-5;
(3) Try any introductory geology or historical geology textbook you can find at the local University Library. Anything published after about 1985 will carry information on the last Glacial Age and the oceans.