Curriculum Units by Fellows of the National Initiative
2006 Volume V: The Science of Global Warming

Global Warming: A Physical Explanation and Implications on Climate

Curriculum Unit 06.05.04, published September 2006
by Eric James Laurenson

This past winter, I was waiting for the furnace repairman at my girlfriend's house. Her house was cold because the heat had been off overnight and January in Pittsburgh is no time to go without heat. John, the furnace repairman arrived and went about his business like a seasoned pro, tool belt slung low around his hips, flannel buttoned up to his neck, odd sizes of bare copper wire protruding from his shirt pocket. Deftly he isolated the problem. "It's the thermostat." He returned from the truck with a new thermostat and proceeded to jerry-rig the spring so that it would work "properly." I could not tell whether he was disabling or engaging the spring, but it was delicate work. As he finished intricately replacing the thermostat on the wall for the third time, after expertly isolating a short in the old wiring that required him to rewire it, my girlfriend arrived home. Although he had indicated that it was an emergency call, that he had several other jobs he had to get to and that it had taken much longer than he expected because of the rewiring, unprovoked, John went off on a tirade about global warming.

"Global warming... what a crock. I've been in the business for thirty-five years and I can tell you that there is no such thing. It's just a lot of talk. I can tell you for a fact that I've put in more furnaces than air-conditioning units in the past year. I've been around a long time," he said with the frost of his breath still slightly visible coming from his animated voice. "Does this seem like global warming to you?" He gesticulated into the air. "Anyways, I can tell you that I know that there is no such thing. The weatherman can't even tell you what the weather is going to be tomorrow. This winter is as cold as any other winter if not colder."

"Actually," my enlightened girlfriend responded, "There is a lot of scientific evidence that global warming in fact results in extreme weather changes, either hot or cold. The current melting of the glaciers is a powerful indication that the Earth is warming-"

"That global warming is just a bunch of malarkey." John interrupted. "I've been in this business a long time and anyone that tries to tell me otherwise is going to get a piece of my mind."

"You're out of your head," I thought. His message that global warming is a myth was absurd but I didn't know how to correct his misconceptions but I thought of my students and wondered how many of them were misinformed about global warming. My students are voting age or soon to join the ranks of the voting public. I want to make sure that they are informed citizens about the issues related to global warming and that they can help to inform others. Now I hope to give a voice to others who find themselves in situations where the science of global warming is discredited by anecdotal evidence and provide them with the scientific evidence.

The science is absolutely clear that global warming is occurring. Temperatures are climbing and the number and severity of storms are increasing. The polar ice caps are melting and the ocean levels are rising. Extreme hot weather as well as extreme cold weather becomes more prevalent. The weather is unpredictable because it is a chaotic system. The extreme increase in greenhouse gases, resulting primarily from burning fossil fuels, is the cause of these potentially catastrophic changes in the Earth's climate.

Overview

In these pages I will attempt to present the physics of global warming, explain the most likely consequences of global warming, address the chaotic nature of weather and why it is difficult to predict and discuss the current scientific theories about the possibility that stress on the climate system of our current rate of production of greenhouse gases could possibly result in a catastrophic change in our climate.

The science is unequivocal that there is global warming and that the Earth's average temperature has increased by nearly a degree Celsius in the past 150 years and the carbon dioxide levels have increased 35%. The energy increase from global warming is 0.1W/m ^{2} per year on the Earth's surface. In 100 years, at the current rate, the Earth's climate system will have increased by 3%, and the rate is increasing. This increase is enough to potentially destabilize the Earth's relatively fragile system.

Although there are many uncertainties about the specifics of global warming, it is clear that it is one of the most pressing issues facing humankind. It is a global issue that must be addressed and mitigated with a sense of urgency that may be unprecedented. The scientific community is beginning to mobilize on this issue and it is essential to create a global, public awareness to address this issue. There is much that is uncertain about the exact implications of global warming but what is clear is that the human production of the greenhouse gases is growing at an alarming rate, is as high now as it has been in 3.5 million years and will exceed the level at any time in the past 50 million years when it doubles the pre-industrial levels in the next 40 to 200 years. Increased greenhouse gases result in a rise in temperature. A rise in global temperature will result in a rise in sea level, an increase in the severity and frequency of storms, drastic changes in rainfall distribution and a change in ecosystems. In addition, there is the possibility that climate may be a chaotic system and that these effects might be magnified and culminate in extreme changes in climate such as precipitating the return of an ice age as some scientific weather models predict.

The primary lesson here is that, although there is a lot that we do not know at this point, the evidence indicates that globally we had better err on the side of caution. Global warming has the potential to annihilate the human race by making our relatively fragile Earth uninhabitable. We must be responsible to our children and our children's children. Are we facilitating their demise by our irresponsible rampant production of greenhouse gases? How do we control our emissions of greenhouse gases before it is too late? Scientists are adamantly predicting that we are approaching a critical point of no return. How do we mitigate this crisis?

The good news is that if we act quickly and with single-minded determination that we do, in fact, have the scientific means to address, reduce and potentially control this problem. Limiting global warming will take a concerted global effort. However, there are enough technological alternatives to the greenhouse producing gas energy sources upon which we are currently dependent for humankind to curb this trend. It is inevitable that the level of carbon dioxide, which is the predominant human made greenhouse gas, will double from the pre-industrial age. The question we are facing is whether that will happen in forty years or two hundred. We are not going to be able to reverse this trend, but the goal is to stop this runaway process and limit the future damage that we are going to inflict upon the planet as a result of global warming. We can not change the past but we do have the ability to control the future. So, now is the time to act. If we do that then given the human ingenuity to solve problems we will buy ourselves enough time to find creative solutions to this problem. It is apparent now to anyone who is able and willing to interpret the scientific evidence that the continued flagrant, irresponsible and unwise production of greenhouse gases will have damaging if not fatal consequences for humanity. So what can we do? Well, first we must understand the problem.

It is also my hope that any teacher who is interested in the issue of addressing the problems of global warming will find within this unit the background scientific information to address the subject in their classroom. This unit is intended to provide relevancy to the study of global warming for high school physics classes and general science classes. The unit can be taught as a capstone on thermodynamics, conservation of energy and waves and the information on climate can introduce chaos theory. The level of instruction can be adjusted to make the unit applicable for general science by presenting the conceptual issues without the mathematical explanation. The primary goal of the unit is to make our students better global citizens who are able to make informed decisions based on current scientific knowledge and to counteract the misinformed myth that global warming does not exist. An informed citizenry is necessary for the protection of our global health. It is my sincerest hope that this unit will be accessible to anyone who wants to become more aware of the scientific issues about global warming.

Specifically this unit is written with my Peabody High School students in Pittsburgh, Pennsylvania in mind. My physics students are juniors and seniors and are among the best students in the school. My general science students are freshmen or are taking the class for the second time because they failed as freshmen. Peabody is 95% African American, 4% white and 1% other. It is a low socioeconomic school in which 98% of the students receive free or reduced lunches and a low performing school in which only 4% of the students passed the state PSSA math test and 20% passed the reading and writing test.

The Physics of Global Warming

The Earth is a rock orbiting the sun. 99.98% of the Earth's energy comes from the sun. The rest is from radioactive decay within the Earth. The sun emits radiant energy in the form of light and other electromagnetic radiation. Light is the specific electromagnetic radiation in the visible spectrum with a wavelength of 400-700 nanometers. Our eyes have adapted to be sensitive to the visible spectrum because our atmosphere is transparent to this range of electromagnetic radiation. This means that visible light is able to pass virtually unimpeded from the sun to the Earth. Our eyes detect the light that reflects off of objects. By interpreting the light rays that reflect off of objects our brain is able to interpret the environment around us. Our eyes and brain construct an image of the world around us by interpreting the amount of light, which is the intensity, the color of light, which is the frequency, and the distance away using parallax. Parallax is the result of having two eyes and being able to obtain depth perception.

Although our eyes are adapted for the visible spectrum, this is only a very minute portion of the entire electromagnetic spectrum. The sun produces the entire range of the EM spectrum from high energy gamma rays to x-rays to ultraviolet to visible to infra-red, which is heat, to radio waves. The infra-red is very important in global warming, but we will come to that in a minute. The key point is that our atmosphere which is made up of nitrogen, oxygen and a small amount of other gases is opaque to a majority of all waves. This means that the majority of EM waves that reach the atmosphere from the sun interact with the molecules in the atmosphere and are absorbed. This is a result of the chemical composition of the molecules. Ozone is a good commonly known example. Ozone, O_3, is a molecule that is particularly effective at absorbing ultraviolet (UV) radiation and its depletion resulted in a "hole in the ozone" which drastically reduced our protection from UV radiation over Greenland. This is only one example but the story of dealing with the ozone problem indicates that the world is able to solve global problems when it is determined to do so. The combination of the different molecules in the atmosphere absorbs most EM radiation.

However, our atmosphere is mostly transparent to visible light. In effect, there is a window that allows almost exclusively visible light to pass through unaffected. Thus the energy from the sun in the visible spectrum reaches the Earth unimpeded, part of which is absorbed and warms the Earth. The Earth that then acts as a black body eventually emits the energy in the form of heat, known in the EM spectrum as infrared radiation. If this energy in the form of infrared radiation were able to leave as it came, the temperature of the Earth would be -25° Celsius. This is below 0 degrees, which is the freezing point for water, so the Earth would be frozen over and uninhabitable for life!

Obviously, the Earth is not frozen over, and in fact the average temperature is around 12°C which makes our existence possible. So what accounts for this increase in temperature? The answer is that the natural greenhouse effect of our atmosphere retains some of the heat that is reradiated by the Earth, raising the temperature enough to be habitable. Let's consider how this greenhouse affect works in detail.

The greenhouse effect is named because the effect of our atmosphere is the same as the process that results in a greenhouse trapping in solar energy. A greenhouse is made out of glass. Glass, like our atmosphere, is transparent to light. This means that the visible spectrum of EM radiation is able to pass through. After entering the greenhouse the light strikes an object in the greenhouse. Some of the light is reflected off of objects and the reflected light is able to pass back through the glass. But some of the light is absorbed by the objects in the greenhouse. The objects in the greenhouse, thereby absorbing the energy, heat up. Eventually the energy that was absorbed is released again, but this is the critical point. When the energy is released it is emitted based on the temperature of the object that is emitting the energy. The sun which is 6000° K radiates EM energy at a much higher frequency as we discussed before and some of that energy is in the visible spectrum. An object which is hot enough to emit light is known as a luminous object. The objects in the greenhouse will be at a much lower temperature, somewhere we suspect in the range between 0°C and 100°C. At this temperature the radiated energy will be in the form of heat, which is EM radiation in the infrared range. This heat radiates out from the objects. The key aspect of the greenhouse analogy is that like our atmosphere, the glass is opaque to infrared radiation. This means that the heat energy will not pass through but will instead be kept in by the glass. Thus the energy in the form of heat which is trapped in will cause the greenhouse to warm up. This is the essence of the greenhouse effect. The atmosphere lets light energy in but the energy that is emitted by the Earth in the form of heat is trapped raising the temperature of the Earth.

A detail of the greenhouse effect is that the atmosphere is only partially opaque to heat, so not all of the heat is trapped in. Some portion of the heat escapes. The temperature rises and eventually a new equilibrium point is established. As is always true there is a conservation of energy, so that the heat coming in has to be the same as the heat going out. What is happening, though, is equivalent to what occurs when you put on a blanket or a shirt. The extra layer traps the heat in, thereby raising the temperature close to your skin, but the outer surface is still in thermal equilibrium.

So the greenhouse affect is a natural consequence of our atmosphere and is a very good thing because otherwise the Earth would not be habitable. For a planet to be habitable, from what we know of the requirements of life, we assume that there must be liquid water so the temperature must be between 0°C and 100°C. There is a very real example of the greenhouse effect making a planet uninhabitable. Let us look at the planet Venus. Increases in greenhouse gases, such as carbon dioxide (CO_2) cause the equilibrium temperature to rise. Without an atmosphere, and assuming an albedo equal to Earth, Venus would be approximately 20°C, but it turns out that the actual surface temperature of Venus is 400°C which is enough to melt lead. So what is different about Venus, which otherwise is very similar to the Earth, that caused it to be uninhabitable? It is a very interesting story and one that we on Earth must take very seriously. It turns out that the early atmosphere of Venus was very similar to the Earth but Venus being closer to the sun was a little bit hotter. The CO_2 in the atmosphere, as on Earth, was partially absorbed by the rocks, which formed a carbonate. But on Venus the temperature was slightly hotter and the process of rocks forming carbonates was temperature dependent so as the temperature on Venus rose the process became less efficient, consequently less CO_2 was absorbed and the temperature rose more. This made the process even less efficient and the levels of carbon dioxide continued to rise until the atmosphere was almost 90-95% CO_2. Therefore, the temperature continued to rise until it reached an equilibrium point around 400°C. However, on the Earth the rocks literally saved us! The rocks were able to absorb enough carbon dioxide to keep the levels of CO_2 in check. The levels of carbon dioxide in the Earth's atmosphere stabilized at 0.03% and resulted in a comfortable average temperature of 12°C. Thus Venus is a huge warning to us of the dangers of increased CO_2 levels and other greenhouse gases.

At the Earth's formation the atmosphere was mainly made up of the light elements of hydrogen and helium with traces of argon and other gases. At the extreme temperatures of the young Earth these light elements were not bound to the Earth strongly enough by gravity and they had enough kinetic energy to achieve escape velocity. Thus these gases escaped. It took billions of years for the Earth to build up its current atmosphere and there is a very delicate balance of greenhouse gases that enables the Earth to be habitable, as we have seen from the example of Venus. The primary greenhouse gases are water vapor, carbon dioxide, methane and ozone. Water vapor is the predominant greenhouse gas and constitutes about 1% of the Earth's atmosphere. The levels of these greenhouse gases have fluctuated naturally, but the current concern is the drastic increase in the level of greenhouse gases from human causes. Primarily the greenhouse gases are the result of the burning of fossil fuels. The level of CO_2 is the primary concern although increases in methane and other greenhouse gases also contribute to global warming. Since the industrial revolution the concentration of CO_2 has increased by 35% and is projected to continuing increasing precipitously unless the emissions of CO_2 is drastically curbed. It is projected from the current climate models that the levels of CO_2 will double what they were before industrialization, 150 years ago, in the next 40 to 200 years!

Although the science of weather prediction is very complicated, and we will go into the reasons later, scientists are in agreement that a drastic increase in CO_2 will result in increased temperatures. Already, in the past 50 years the Earth's average temperature has risen more than a half a degree Celsius and the rate is accelerating. In addition, this is only half of the predicted amount as a result of the time delay for the oceans to heat. Although there is a lot of uncertainty about the exact amount, the best predictions indicate that the average global temperature will rise between 1.5°C and 4.5°C according to the IPCC (Intergovernmental Panel on Climate Change), when the pre-industrial level doubles. Although this may not sound like a lot it has been shown that the ice ages were likely the result of a change of less than 4.5°C! It is possible that it was even less because the amount of warming is not consistent across the globe. The poles experience as much as ten times the amount of warming at the equator. So we are facing a very grave situation and something must be done right away. The consequence of such an increase in the average global temperature is potentially catastrophic. This might seem hard to believe since the daily temperature can vary by as much as 20°C. However, the difference is that we are talking about the average temperature of the entire globe including the poles. Even though the daily and seasonal temperatures vary greatly, the average global temperature is remarkably constant! Virtually all of the energy that heats the Earth comes from the sun and the energy that reaches us from the sun is relatively constant; therefore, the overall average is relatively constant although the local temperatures can vary dramatically. Next let us consider the implications of the increase of global temperatures as a result of global warming.

The Consequences of Global Warming

The rise in temperature will have dramatic consequences. The four immediate major affects as a result of the increase in temperature due to greenhouse warming are the rise of sea level, the increase of severity and frequency of storms, the drastic change in rainfall distribution and a change in ecosystems.

The most significant effect will be the rise of sea levels. Sea level will rise as a result of the heating of the oceans which will cause the thermal expansion of water because a liquid at a higher temperature takes up more volume. In addition, the increased temperatures will cause the continued melting of the polar ice caps and Greenland. The melting of these land based ice sheets will add additional water to the ocean whereas sea based or floating ice does not add to sea levels. This is because like in a glass with ice cubes, floating ice cubes melt without causing the level of the water to rise, but a glass with a stack of ice cubes in it will melt, thus increasing the level of water and overflowing the glass. It is very difficult to predict the exact amount of the increase in sea level but it is certain that coastal areas and areas close to current sea level are in jeopardy of being under water. It is projected that hundreds of millions of people could be displaced by rising sea levels.

The melting of the glaciers has an additional implication. Ice is white and is very highly reflective. The scientific term for reflectivity is albedo. A perfect mirror has an albedo of 1.0 and a perfect blackbody that reflects nothing has an albedo of 0. Ice has a very high albedo close to 0.9. This means that the light that strikes the ice is mostly reflected. The light that is reflected is therefore not absorbed by the Earth and therefore does not contribute to the Earth's energy. In addition, reflected light retains its spectral qualities so the reflected light is in the visible spectrum which is transparent to our atmosphere and thereby is sent back out into space unimpeded. When the ice melts, however, it becomes ocean and the ocean conversely absorbs almost all radiation. Thus the ocean has a very low albedo around 0.1. The light then that would have been reflected is now absorbed. This results in a further increase in the temperature and the oceans at the poles heat up much more rapidly than other parts of the globe.

The increase in global temperatures also warms the oceans. The increase of both air and sea temperatures results in more frequent and severe storms. Unfortunately, this is abundantly clear by last year's hurricane season. Last year marked the record number of hurricanes. Although it is impossible to say whether hurricane Katrina is the immediate consequence of global warming, it is clear that global warming is a contributing factor. The increase of temperature will result in a greater number of more powerful storms.

Global warming also has some paradoxical affects. Although some areas will experience more severe rainfall other areas will be plunged into draught. The rainfall will be redistributed around the coastal areas as a consequence of greater temperature differences between the air and land masses. However, the inland areas will undergo greater evaporation from increased temperature thus resulting in drought. These affects will be unpredictable and erratic. Thus we will see a greater increase in drastic weather, so extreme weather can be an indication of global warming.

Inevitably, ecosystems are also affected by the increase in temperature. Temperate zones are shifting thus causing ecosystems to attempt to adapt. Some species will be able to adapt by moving but others will not. This is causing the extinction of many species. It will also affect humans by altering the location in which crops will grow.

The Uncertainties of the Science of Global Warming

Although much is known about the physics of global warming there are many uncertainties in regard to the amount of warming that will occur. This is the result of the complexity of the Earth's system, the internal positive feedback processes, the lack of long term global temperature and CO_2 records, variations in solar output and the Milankovitch cycles, the affect of aerosols and the affect of the ocean as a sink for carbon dioxide.

The Earth is a remarkably complex system that involves atmosphere, land masses, oceans and ice formations. There are so many factors that affect this massive thermodynamical system. Some of the processes are understood, but many of these processes have a high degree of uncertainty and our current modeling is insufficient to make accurate predictions. One of the primary sources of the uncertainty is the positive internal feedback processes. In a positive feedback process it is necessary to understand how each component of the global warming problem affects the other components. An example is the role played by clouds. Water vapor contributes the most to the greenhouse affect. As temperatures increase, there is more evaporation. Water vapor forms clouds. Clouds increase the albedo of the Earth by reflecting more light back into space and therefore decrease the fraction of the solar energy absorbed. This is evidenced by the fact that clouds are white, which means that they are reflecting a lot of light. By reflecting the incoming sunlight, unlike the light that reaches us from clouds, clouds could have a cooling affect on the Earth. On the other hand, clouds are a greenhouse gas and therefore cause a heating of the Earth. This heating, however, results in a melting of the Earth's ice which decreases the albedo of the Earth and results in warming. So the answer is not obvious whether cloud formation has a warming or cooling effect. This is the challenge of understanding positive internal feedback processes.

We only have an accurate record of global temperatures for the last one hundred and fifty years and CO_2 records for the past sixty years. Prior to that time we must rely on other methods to determine the temperature and CO_2 levels. Remarkably we can acquire these in the ice cores of the poles and Greenland that go back 650,000 years. This can be done because the ice can be dated. There are two methods of dating the ice. The first method is to read the signature caused by the regular magnetic fluctuation of the sun that has an average cycle of 11 years. The second method is only accurate for a much shorter time, but because the ice thaws and melts every year, there is a mark in the ice like the rings of a tree. The temperature can be obtained because there is an incredibly accurate correlation between temperature and the concentration of the ^{18}O isotope. The carbon dioxide level is obtained by analyzing the air trapped in bubbles in the ice. The limitation of this is that although we are able to get very accurate readings of temperature and carbon dioxide concentrations we only have the temperature at a few locations on the globe where there are long standing glaciers. Local temperatures are variable so this limits our ability to project and to create models from the data.

There are some significant uncertainties about the influence of the sun on the Earth. There are variations of solar output. The sun's luminosity was 70% when the Earth first formed and is increasing by 6% per billion years. The climate is very sensitive to the sun's variability. The changes in the sun's position is known as the Milankovitch cycle resulting from precession, rotation of the semi-major axis and the change of eccentricity of the Earth's orbit. The Milankovitch cycle is very periodic and it's signature is evident in the long term climate and in fact correlates strongly with the occurrence of ice ages.

Aerosols, which are small particles that remain in the atmosphere, are another source of uncertainty. They are reflective of the solar energy but their exact affect is unknown. Although burning fossil fuels result in aerosols, the majority of aerosols are the result of volcanic eruption. More research needs to be done to determine the effect of aerosols on global warming.

The ability of the oceans to absorb CO_2 is a huge uncertainty in the global system. It has been assumed that the oceans are able to absorb large quantities of CO_2. This appears to have been the case in the past but there are indications that the oceans are warming, although there is a time lag, and that an increase in temperature could cause the oceans to release CO_2. This is the reverse of the expectation for climate models and would significantly increase global warming. In addition, it is clear that the oceans are being drastically affected by the absorption of CO_2 because the pH of the oceans is dropping since CO_2 is acidic. This decrease in pH is reducing the coral reefs ability to capture CO_2 in the form of carbonates thus increasing the atmospheric concentrations as well. The human production of greenhouse gases is having a global impact with consequences beyond our ability to foresee. It is time for us to begin to limit the damage that we are doing to the planet and control the production of greenhouse gases before it is too late.

The Chaotic Nature of Weather and the Difficultly of Prediction

---

We have considered the scientifically accepted predicted affects of global warming on our global system given that our climate is stable. The climate is our average weather. Now let us look into the chaotic nature of weather which makes it impossible to predict weather in the long term. We are reliant on assuming that our climate is stable in order to make long term predictions, however, there are many scientists that believe that in fact our climate may not be stable. The climate may be chaotic as is the weather and there are very serious implications. If the climate is chaotic, then small changes in temperature could result in very drastic effects in the climate. This means that the climate could vary dramatically. Then, instead of a few degrees change in our climate, those forces could possible result in catastrophic changes. Our Earth is only habitable in a very narrow range of climate. A drastic change in climate could result in the Earth becoming uninhabitable or frozen over. It is unclear, but many climate models predict that our climate is not stable. Before we can get into these details let us first look at what it means that the weather is chaotic.

Weather is a chaotic system. Chaotic systems are deterministic, non-linear systems that are extremely sensitive to initial conditions. With linear systems, changes in initial conditions have a proportional affect, so a small change in input will result in a small change in output. In a chaotic system, however, very small changes in initial conditions can, and often do result, in totally divergent outcomes. This is known as the butterfly affect and is often explained by the example that the flapping of a butterfly's wings can eventually propagate into a hurricane if the conditions are right. In other words, you can not predict from where two points start where they will end up in relation to each other. An analogy for chaos is a piece of taffy being made. Two points that are close together in the beginning, as taffy is being made, are stretched and folded back on themselves and can end up in totally different places. Also points that are far apart from each other may end up very close. It is impossible to tell. In chaotic systems, any change in the initial conditions can result in totally different results. Chaotic systems are known as non-linear equations and great complexity can result from simple equations.

Chaos was first discovered using weather modeling. This was definitively established by Edward Lorenz. He was modeling the weather on a computer. In one of his simulations he wanted to rerun a previous weather pattern. He reprogrammed his computer with the same line of data from a previous run. However, after a short time the outcome completely diverged and was unrecognizable compared to the initial run. Lorenz was in disbelief because he thought he had programmed in the exact same data. However, it turns out that the computer data was slightly rounded off to the fourth decimal place. Even though his data was very similar, Lorenz discovered that in a chaotic system like the weather, a miniscule difference, even one part in a thousand can provide entirely different results. This was the beginning of chaotic modeling of the weather and it is the reason that it is so difficult to predict the weather. Even with our most powerful computers making millions of calculations a second we can only reliably predict for a few days because once the model is started the errors grow with time. This is the result of never knowing the initial conditions perfectly. Consequently, the further you get away from the starting point the more your model will diverge from the actual events. Chaotic systems often appear random but on short time scales it takes time for the errors to diverge. Thus our predictions are more accurate in the short term and become significantly more unreliable with time.

So why do we spend so much time trying to predict the weather? Well, as we have seen, storms often have a devastating impact and advanced warning is essential to preparing for emergencies. In addition, people like to be able to know what to expect. Consequently, tremendous resources have been spent on trying to develop the most accurate computer weather models possible. We are all familiar with our local weather prediction systems. As hard as we try, however, our weather models are still only reliable on the short term. But as our computer models improve, by comparing the predictions with the actual results, and as we get better data, that is more accurate and comprehensive, we are able to increase the accuracy of our predictions. The chaotic nature of the weather, though, will always limit our ability to make long term predictions. However, there is sufficient motivation to keep improving our ability to predict the weather.

It is clear that the weather is a chaotic system and there are plenty of other examples of chaotic systems. For example the magnetic fluctuations of the sun are chaotic. However, they reach a maximum intensity every 8 to 13 years, but on average the cycle is remarkably constant at 11 years per cycle. Another characteristic of a chaotic system that distinguishes it from randomness is that chaotic systems tend to stay around certain values, known as strange attractors. Although it is still debated by scientists, there is building evidence that our climate is also a chaotic system. Now let us consider what it means if our climate is chaotic and what implications that has for us in regard to global warming.

The Implications of a Chaotic Climate

Climate is the average of our weather. Our climate is variable. According to Jose Rial "The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm." (Rial, et al,11) The Earth is a rather fragile system, meaning that the range of temperature to maintain a habitable climate is very small. There have been fluctuations that have resulted in the various Ice Ages and there is a question as to whether these are the result of the Milankovitch cycles of the changing motion of the Earth relative to the sun. Although there is a high correlation, it is possible that the chaotic climate has actually magnified these and other events. If climate is highly chaotic then there is the possibility of multiple attractors and the climate could switch from one attractor to another. If this is a possibility then we have to be very careful about forcing our climate into another regime. A chaotic system stays around a value unless it is given enough of a push and then it can switch to another average value. It is possible that the stress of drastically rising temperatures could be a force that results in just such a change. The climate that we now have is suited for human habitability and if there was a change in climate it is likely that the climate would be less habitable or totally uninhabitable. So let us consider the evidence that the climate is chaotic.

Climatologists have created global computer models for the long-term behavior of the Earth's atmosphere and oceans. James Gleick indicates that the climatologists "have known for several years that their models allow at least one dramatically different equilibrium. During the entire geological past, this alternative climate has never existed, but it could be an equally valid solution to the system of equations governing the Earth." (Gleick, 170) This is known as the White Earth climate because the Earth is frozen over and the high albedo of the ice would result in very low temperatures. According to Gleick the computer models have a strong tendency to fall into the White Earth equilibrium and many climatologist wonder why it has not happened. Possibly it is just chance but in these scenarios it takes a large amount of energy to force the system into another climate. Is it possible that global warming is a sufficiently large push? According to Ian Stewart, "Indeed there is a good case for identifying 'climate' with 'attractor', and if we do then what we are discussing now is climate change. And then it is not the flap of a butterfly's wing that should concern us, but the massive build-up of human-made greenhouse gases." (Stewart, 250) The possibility of global warming changing our climate is a very real concern.

Lorentz also introduced the concept of "almost-intransivity" in which a system fluctuates around a given average for a period of time but unpredictably switches to another average value. Many climate models are susceptible to "almost-intransivity." Gleick suggests that this might explain why the Earth has drifted in and out of Ice Ages and that "The Ice Ages may simply be a byproduct of chaos."

Another example of a possible consequence of the chaotic nature of the climate has to do with the Thermohaline circulation, which is the circulation of the oceans including the Gulf Stream. The evaporation of the ocean results in a cooling of the water and a higher concentration of salt. Since cold water is denser than warm water as a result of its thermal properties, and salt water is denser than fresh water, the water sinks. This acts as a huge pump for the ocean and results in a "conveyor belt" across the globe. A drastic rise in global temperatures results in the melting of glaciers in the North, which is fresh water. This reduces the salinity and thus the density of the cold water reducing the water that sinks in the North Atlantic which could shut down the global pump. It is likely that in the past this stopped the circulation of water (Karl and Trentberth, 1721-2). The Gulf Stream is essential for the warming air currents that rise the temperature of much of Europe and the stoppage of the Gulf Stream resulted in Europe going into an ice age for hundreds of years. It is possible that the initial temperature increase was not sufficient to have this effect of melting the glaciers sufficiently, but that the chaotic nature of the climate magnified the effect. This chaotic event has occurred often throughout the Earth's history. The change from warm to much colder and longer intervals were always extremely rapid. Chivalet indicates that "The climate during the last glaciation was bistable. The system had a chaotic behavior, and alternates between two very different states of equilibrium. Both states and the abrupt changes occurring between them seem to have been strongly controlled by drastic changes in the thermohaline ocean circulation." (Chivalet, 58) The projected temperature increases by current climate models appear to be sufficient to once again stop the thermohaline circulation and send us into an unpredictable global climate.

John Houghton suggests that the climate is not strongly chaotic and that like the Milankovitch forcing, "the increases in greenhouse gases will also result in a largely predictable response." (Houghton, 1372) However, taking the stoppage of the thermohaline circulation into consideration, the changes in climate hardly seem predictable.

There is the possibility that our current rate of production of greenhouse gases could possibly result in a catastrophic change in our climate. Certainly there is enough evidence that we should be cautious. In addition to the predictable and devastating affects that global warming is likely to have as the temperature rises there are also the much more unpredictable consequences of putting stress on a chaotic system. A possible consequence of our continued massive production of greenhouse gases is the change in our climate. Humankind and all life is dependent on our climate remaining habitable and given the fragile range in which life is possible we are forewarned. We must be cautious because we may be approaching a point of no return. We only have one place to live right now, so we had better resolve to take care of the Earth's environment and its climate. The cosmos is certainly indifferent to our plight and our fate may well be in our own hands.

Objectives

My main objective is to teach my students about the main issues of the science of global warming. I want my students to have a grasp of the scientific facts that explain global warming, a conviction that global warming is a pressing issue for all of us, an ability to speak up about global warming and to discourse intelligently about this challenge, and the desire to participate in the public discourse. The students will get a basic understanding of global warming and be able to incorporate that knowledge into a greater understanding of physical science (S2). Students will improve their capacity for making discerning judgments about issues related to science and will be able to appreciate the scientific method as a valuable and useful approach to decision making. The students will be able to use their observations to evaluate the veracity of knowledge and be able to identify issues that are still unknown (S1, S5). The students will be able to understand the evolving nature of science and the method that scientist use to make truth claims (S7). The students will appreciate the role that the advances in technology have played in the study of global warming and be able to access internet resources (S9). The students will acquire the terms and language to discuss global warming (C5). The students will be able to communicate their ideas, express their opinions, and defend the relative reliability of different theories. The students will engage in class discussions (C6, C7, C8). The students will improve mathematical skills in understanding formulas, calculating results, representing their data graphically and comprehending the implication of mathematical expressions (M1, M2, M4, M5, M6).

Strategies

This will be an inquiry based unit. I will begin this unit on global warming by asking the students to list what they consider to be the top five concerns facing us as human beings on this planet. I will ask them why they have listed these issues as their top five. I expect that the top five will be related to their own personal concerns of safety and well being. It is my hope to be able to open up a discussion of the students' personal concerns in order to begin to stimulate a global concern. Pittsburgh is not likely to be significantly directly affected by raising sea levels, increased storms or changing rainfall, although this is possible. Instead my emphasis is going to be on attempting to instill in students a sense of global perspective. All people must share the Earth and the poor are always the most vulnerable to fluctuations. So how do we as a people take responsibility for the global community? I will establish the relevance by stressing the need for community.

First I will ask them how much energy they use during the year. What do they need energy for? Food, transportation, heat, to have things made, the trash generated… I will guide students to realize how many resources they use and indicate that we use more energy in the US than anyone else. More than Africa and Asia combined. Where does all of this energy come from? Mostly the energy is from fossil fuels. We burn gas and oil to create most of our stuff. This leads to global warming.

What is the maximum temperature that we can live at? What is the minimum temperature that we can live at? The Earth on average is 12°C. So how can a few degrees make a difference? Rising sea level, increased frequency and severity of storms, redistributed rainfall, changing ecosystems, economic consequences…

Mostly, though, our concern must be that we don't have anywhere else to live. The Earth is our only home and there is the possibility that if we abuse it, it might no longer be livable for us. There is the real possibility that we could cause another Ice Age. If we mess up our climate there is no where else for us to go. We must all live on this planet so we must take care of it.

I will utilize constructivist methods to stimulate interest in global warming. I will do this by giving the students some experiential knowledge of global warming. First we will do an experiment on the Greenhouse effect. By shining a light on a sealed glass jar we will compare the temperature of the air inside the glass jar to the temperature of the air outside. This will indicate that greenhouse effect exists. I will have the students compare what happens if we paint the bottom of the jar white and what happens if we paint it black to compare the effects of reflectivity and albedo. I will indicate that our atmosphere acts the same. It is just like a greenhouse.

Next I will have several of the students put on body suits during class. Without increasing their normal activity we will discover that putting on an extra layer, especially if it is well sealed, will result in internal heating.

I will demonstrate the concept of the thermal expansion of the oceans by heating up a water thermometer. Why happens to the water? Why does it expand? What does this have to do with the oceans? What will happen to the oceans as they heat up? Where will the water go?

Then we will calculate the expected temperature of the Earth and Venus. I will attempt to get them to derive parts of the formula by prompting them about the required components of the formula: namely the energy output of the sun, the distance the Earth is from the sun, the reflectivity of the Earth, and the surface area of the Earth. Using this we will calculate the temperature. I will also have my students utilize this to algebraically derive the simplified version of the formula. Having done this we will determine the expected temperature on Venus and compare. Venus would appear to be habitable whereas the Earth does not. However, we know that the opposite is true. Why is this? I will let the students speculate. If they don't suggest it I will remind them of their lab and get them to realize that it has to do with our atmosphere and the greenhouse effect. Without our atmosphere we would not be here!

So what has gone wrong? Why are we concerned about the greenhouse effect? I will ask my students these questions. Let's consider the Earth. Now let's build a model. I will have the students build a model of the sun and the Earth. What happens between the sun and the Earth? How is the energy transmitted? What happens to the energy when it reaches the Earth? How do we see? What does this tell us about our globe? Let's look at some pictures of the Earth? What is the shape of the Earth? What do we see when we look at the Earth from outer space? What does our atmosphere do? Have you heard of the hole in the ozone? What was that? Why do we get a sun burn? When do we get burned the most? At what time of day? What does this tell us about light? How do we include what we know about the atmosphere in our model of the Earth? What did we learn from the "body suit" activity? Is our atmosphere like a blanket? How can we include this in our model?

Let's build a model of our chaotic climate. The students will build a rollercoaster with multiple high and low spots. We will build these roller coasters out of tracks. I will give each group a ball and have them place it in a low spot. Let's label the lowest spot -25°C then label the middle point 12°C and the highest point 40°C. What happens if you give it a very small push? What happens if you give it a slightly bigger push? What does it represent when the ball ends up at a different "temperature"? This is an indication of our climate change. If our global warming provides enough of a push maybe we it will change our climate? What would the consequence of a drastic change in our climate be? Would we be able to survive?

The students will have enough basic knowledge at this point that I will print up the background knowledge and provide it to them. After they have familiarized themselves with the scientific information I will have them split into two teams and have a debate about global warming. Half of the students will defend the statement that global warming is a serious issue and we must do something to prevent a global disaster. The other half of the class will make the argument that global warming is a myth and there is nothing that we need to do. The debate will last twenty minutes. Then we will discuss how the issues were most effectively addressed.

The culminating event is going to be for students to write the mayor of Pittsburgh and explain why we should be concerned about global warming. The paper will be a persuasive essay to convince the mayor to join other cities in the support of the Kyoto Treaty. I will provide them with information about Pennsylvania and other states that have already joined. This exercise is meant to empower the students and encourage them, since they are nearly of voting age, that local government is a powerful means of societal change.

Lesson Plans

Lesson Plan I: Lab on the Greenhouse Effect

This lab will demonstrate the greenhouse effect. The materials that are needed are a glass jar with a cotton swab to seal the opening, two thermometers and a movable light source. The procedure for the lab is to have the students put one of the thermometers inside the glass jar and seal it with the cotton swab. The students should then position the light source so that it shines on the glass jar and the second thermometer which is placed next to the glass jar. An equal amount of light should laminate both thermometers. The students should record the temperature of each thermometer before shining the light on them and then every 30 seconds for ten minutes. Once the students have taken all of their data they should plot a graph showing the readings of both thermometers. The students then compare what happened to the temperature of the two thermometers. Which one heated up the most and why? How does this demonstrate the greenhouse effect?

A variation on this lab is to include the factor of albedo which is the measurement of reflectivity of surfaces. This time have the students place two jars side by side with thermometers sealed inside of them. Have the bottom surface of one jar painted white and the other jar painted black. How does this effect the temperature readings? Plot your results.

Lesson Plan II: Math calculations of Energy formula of the Earth- Determining Earth's temperature

This lesson is designed for the students to use accessible mathematical formulas and known values to calculate the temperature of the Earth and Venus from the heating of the sun. These calculations are to determine what the average temperature of the Earth would be without the greenhouse effect. The results are dramatic because without the greenhouse effect the Earth would be frozen over and Venus would be comfortable. However, with the natural greenhouse effect the Earth is habitable and Venus is hot enough to melt lead.

To calculate the temperature of the Earth you use the following equation

$$\frac{L_s}{4\pi d_S^2} \bullet \pi r_E^2 \bullet (1 - A) = 4\pi r_E^2 \sigma T^4$$

L_s- luminousity of Sun= 3.86×10^{33} erg/sec

A - albedo = 0.39

d_s - distance of Earth from Sun = 1.496×10^{13} cm

r_E - radius of Earth = 6,378 km

Σ - Stefan-Boltzman constant = 5.67×10^{-5} erg/cm^2 deg^4 sec

1st term -"energy flux"

2nd term - cross-sectional area of the Earth

3rd term- amount of energy absorbed

Equals:

Surface area of the Earth x Boltzman constant(energy per meter) x temperature to the fourth power

Solving for temperature: (Πr_E^2 cancels leaving:)

$$T^4 = \frac{\frac{L_s}{4\pi d_s^{\,2}} \bullet (1-A)}{4\sigma}$$

Substituting in the values gives:

$$T^4 = \frac{4x10^{33}x0.61}{16\pi x5.7x10^{-5}x(1.5x10^{13})^2}$$

$$T^4 = \frac{4000x0.61x10^{30-(-5)-26}}{16\pi x5.7x2.25} = 3.78x10^9$$

T= 248K = -25°C

Now use the same equation to calculate the temperature of Venus.

$$T^4 = \frac{\frac{L_s}{4\pi d_s^{\,2}} \bullet (1-A)}{4\sigma}$$

Distance of distance of Venus from the sun: d= 0.72 AU

Although the albedo of Venusis currently 0.76, if no clouds were there (no atmosphere), the albedo should be similar to Earth, 0.39

A simplified formula is:

$$T_{planet} = 278\left(\frac{(1-A)}{d_s^{\,2}}\right)^{\frac{1}{4}}$$

where d is the distance from the planet to the sun in units of AU (the mean distance between the sun and Earth)

Derive this formula and solve for T_{Venus}=

The students discuss the implications of their calculations of the temperature of the Earth from the sun's luminous heat and the temperature of Venus. Without the greenhouse effect we could not live on the Earth.

Lesson Plan III: Chaos Demonstration of Multiple Attractors

Provide the students with materials to build a rollercoaster like track that will allow a ball to roll from high spots to low spots. Have the students build the track with multiple low and high spots. Mark the high and low spots with relative temperatures ranging from (-25C) to (12C) to (100C). These temperatures represent the climate and indicate the average temperature of the Earth. Demonstrate how a ball will tend to stay at a low point which is a "strange attractor" unless it is given enough energy to clear the high point and then it will settle into another low point or "strange attractor." Indicate to the students that these low spots are stable states that tend to remain the same. The push that you give the ball to get it to move are the external forcings such as global warming that change the temperature of the Earth's system. So far we have remained in a stable climate, but what would happen if our ball, "the climate", were to end up at a higher or lower state?

What would it mean for us if the climate were to change to -25C or 100C? What would happen to life on our planet?

Additional Lesson Plans

Using Verneer Probes demonstrate how luminousity varies with distance.

Possible clothes layering activity- get a body suit to demonstrate how it increases the temperature within- green house affect- explain that this is only an analogy because it is the result of convection instead of radiation.

Water Thermometer for thermal expansion- demonstrate that the sea level will rise significantly by the affect of thermal expansion. Heat a water thermometer to show that expansion due to heat is a significant affect.

Global Warming Debate: What is the likely effect of Global Warming and What can we do? As a summary of the unit the students will debate what they think the likely results from global warming will be and what we can do to control the impact. What do we have to do to limit the effects of global warming?

Write your Mayor. Encourage them to join the cities concerned about global warming and committed to making a difference.