The Earth System

Our account of 4.6 billion years of Earth history is bound to involve a great deal of speculation and best guesses. We can reconstruct a broad outline of the Earth's past by analysing different kinds of geologic evidence which give us an indication of what the environmental conditions would have been at the time of deposition. Techniques for reconstructing the past have become increasingly sophisticated and as we move closer to the present more indicators and more data is available. What we can say for sure, if we accept that we are not subject to an omnipotent God who is interfering haphazardly with the physical laws of the universe, is that the Earth's climate has changed ever since it came into existence and that it has passed through various kinds of climate regimes. We know that there are many factors which influence the climate, including solar radiation, Earth's orbit around the Sun and the periodicities of its spin axis, the drift of the continental plates, circulation of the winds and oceans, atmospheric composition and biological activity. These factors never remain the same and therefore the climate changes. Many of the transformations from what we today regard as the hostile environment of the Hadean to the present relatively warm interglacial climate are mysteries that will keep us busy for as long as we care to investigate the past. By describing and comparing the longer periods of quasi-stable climates we arrive at ideas about what are the mechanisms of change. And combined with observations of the present climate we can make inferences about the direction and the strength of future climatic changes. But what is perhaps most important in grasping the Earth system is the picture it provides of the environment in which our lives take place. It is the context for our history as a species and it provides the setting for the stories that shape our cosmology and individual identities. Observation of some of its processes might also reveal something about ourselves and our position in the great system.

The Earth viewed as a system is the great collection of physical, chemical and biological activities that are involved in the processes through which solar radiation is absorbed, recycled and emitted back into space as heat energy. These processes occur within and between the four major system components: the biota, the atmosphere, the hydrosphere (including the oceans, fresh water and ice) and the lithosphere, solid Earth. In its present state the Earth system regulates to a mean surface temperature of about 14 ^{o}C. Imagining that the Earth system is in steady state, i.e. that there is no surface temperature change, we can assume that the energy absorbed by the Earth is equal to the energy emitted (and we will do so in order to work our the global energy budget). Effectively, this will not happen until the Earth system ceases to be – the ability of the Earth to 'metabolise' implies that the system is always in fluctuation far from a steady state where there is no more internal motion. It is the imbalance in the global energy budget that drives climate change. It is getting warmer because the incoming solar energy exceeds the outgoing heat energy by a tiny amount. We can estimate the global energy budget and the greenhouse effect from the equation:

Energy absorbed by the Earth system = Energy intercepted – Energy reflected

With the help of physical laws and empirical observations it is easy to derive the values for this simple climate model, and doing so will help us understand the functioning of the Earth system better.

In this model we can assume that Earth's surface temperature depends on the incoming solar flux, reflectivity of the surface (albedo), and the greenhouse effect. As mentioned above, the energy absorbed by the Earth is roughly equal to the energy emitted. Using a physical law for the energy emitted by a blackbody, *the Stefan-Boltzmann law*, we know that the energy flux, F, from a blackbody is related to the fourth power of the body's absolute temperature, T:

$$F = \sigma T^4$$

where σ is a constant with the value of 5.67 x 10^{-8} W/m^2/K^4. Temperature is usually described in Kelvin so to get degrees Celsius we have to subtract 273. The Earth emits energy over its entire surface area, 4 times π times Earth's radius, R, squared. This means that the left hand side of our equation for the global energy budget is $4\pi R^2$ x σT^4.

Although solar radiation fluctuates over time, we know that on Earth today it is close to 1367 Watts per square meter (W/m^2) – this is called the 'solar constant', S. The part of the Earth's surface that receives this radiation at any time is that area which faces the Sun – from the Sun the Earth would look like a circle with an area of pi times the radius of the Earth squared, πR^2. So the energy intercepted by the Earth is equal to $\pi R^2 S$. The energy reflected by the Earth is this same amount times the albedo, A. Planetary albedo is roughly 0.31 (this means that 31 per cent of incoming solar radiation is reflected back into space and 69 per cent is absorbed by the Earth). Thus the right hand side of our equation becomes $\pi R^2 S - \pi R^2 SA$, or $\pi R^2 S\ (1 - A)$.

Writing out the whole equation and cancelling out $\pi R^2 S$ on both sides we get:

$$\sigma T^4 = S/4\ (1 - A)$$

This is an expression of the balance between incoming solar radiation and outgoing infrared radiation in the Earth system. Entering the values above we find that T = 254 K, equivalent to -19 ºC. This is the effective radiating temperature. The difference between this value and the observed surface temperature of 14 ºC is 33 ºC – this extra warming is caused by the greenhouse effect, the absorption of radiation from Earth by certain gasses in the atmosphere. Without this warming effect the Earth would be much too cool for life as it exists today.

From this simple model we get a sense of the relationship between solar radiation and emission of long-wave radiation back into space. We see how the reflectivity of the Earth's surface influences the energy balance and we might expect that factors like more or less ice and snow, the extent of forests and deserts, cloud cover, and the oceans play a role in this relation. The energy balance model can be extended to include a layer (or more) representing the atmosphere to make a model estimate of the greenhouse effect. We will not do that here but the atmosphere is implicit in the energy balance, it is the structure and the composition of the atmosphere which determines how strong the warming effect is. The incoming energy is not evenly distributed, the Earth receives more energy around the Equator because this surface area is perpendicular to the incoming sunlight and this energy is dispersed towards the poles by the circulation of the winds and the oceans. Earth's interior also contributes a small amount of energy to the global energy balance through geothermal heat which leaks out from volcanoes and underwater vents (volcanism is also crucial in the recycling of carbon by releasing gases from Earth's interior into the atmosphere).

We begin to see how the patterns of energy distribution drive the global climate and the roles played by the components in the Earth system. We can visualise the system as extending from the top of the atmosphere, where there is an exchange of atoms with space, to somewhere in the interior of the planet, where minerals are temporarily stored before they pass back into the system above ground. It is an open system in that it interacts with the greater system within which it is placed, but for practical purposes, like calculating the energy budget, we often consider it to be closed. To understand the interactions of the system better we will look at some of its parts in a little more detail. But first, let us imagine a water molecule drifting downwards towards Antarctica in the form of a snowflake.

In late winter our water molecule lands on the Ronne Ice Shelf in West Antarctica. It is quickly covered and for a long time it just sits by the edge of the ice shelf buried under millions of other snowflakes. Some of the other water molecules here have been trapped in the ice for a very long time. They fell as precipitation thousands of years ago further inland and have since moved towards the sea in a slow moving ice stream. After a couple of years our water molecule flows into the Weddell Sea in a tiny iceberg which melts before it reaches the open sea. The low temperatures and the high salinity in the Weddell Sea make the water here is very dense, and the water molecule sinks down the slope of the basin as part of the flow of Antarctic Bottom Water. This current circles Antarctica and flows northward along the bottom of the sea. The downward flow of bottom-water is what drives deep ocean circulation. The molecule travels in this current for a couple of hundred years before it warms and rises to enter surface circulation where it stays for two thousand years. One day in the Bay of Bengal, off the east coast of India, the water molecule reaches the surface where it is heated by the Sun and evaporates to form part of the moist air of the Indian monsoon. This high pressure air is drawn inland towards lower pressure regions in central Asia and as our molecule rises it cools and forms part of clouds moving northwards. Somewhere over Uttar Pradesh the molecule loses enough energy to condense and falls as a rain droplet into the river Ganges. It enters the Ganges Canal which irrigates the Doab region and eventually it is absorbed in a wheat field and the water molecule is split to form hydrogen ions and oxygen.

We could of course extend this story indefinitely. The water molecule could cycle between the various water reservoirs millions of times, staying in each reservoir for varying lengths of time (the average time spent in each reservoir is called residence time). E.g., the residence time for the ocean is 3200 years, for shallow groundwater it is between 100 and 200 years, and for the atmosphere it is 9 days. Although this flow between various reservoirs may appear random it is part of an ordered circulatory system. The circulation of the winds and the oceans redistribute solar energy across the globe and the circulation of gases and minerals move nutrients and waste products around the system. Water cycles continuously between the atmosphere, the ocean and land and in doing so it transfers energy, nutrients, and waste between the different components – it is the principal medium for exchange of energy and matter in the system. To change ice to water or water to vapour requires energy. This energy is stored in the water molecules in the form of latent heat which is released back into the environment once gaseous water condenses or liquid water freezes. These processes we experience as weather (snow, rain, clouds) and they affect the energy budget of the atmosphere, e.g. condensation of water vapour can release enough energy to cause a tropical cyclone. Water is also a powerful greenhouse gas and the amount of water vapour in the atmosphere directly influence the magnitude of the greenhouse effect.

The interconnected nature of the Earth system should be clear to us now, and we begin to see how the Earth's circulatory systems regulate temperatures by distributing energy around the system. But we can make another point from this example. Let us imagine that the hydrogen from our water molecule from before forms part of a carbohydrate in the wheat, which is subsequently harvested and processed into flour that someday somewhere is made into bread. This bread is then eaten by a human being and the carbohydrate containing our hydrogen is used to form cartilage in that person's body. We see that the entities we have been considering (the water molecule and the hydrogen atom) form integral parts of greater entities, or wholes, (like weather systems, carbohydrates, and bodies) and that their behaviour depend on the particular system of which they are part. Together these wholes, nested within each other, form patterns that are interdependent in every movement and exchange of energy. The division into molecule, cloud or wheat field occurs when we perceive and speak about the molecule, cloud or wheat field, not as a revelation of some innate property of these wholes.