1
Introduction

Nature is at its end: we need to put something in its place. During the past decade the validity of this statement has been debated within a small part of the scientific community, without unanimous agreement. More recently, the discussion has moved beyond that small group, into the political forum. As the debate has broadened it has become less rational, more intuitive; opposing viewpoints are stated forcefully, sometimes with beauty, often in anger. Emotional vision can be deeper than rational sight, but both emotion and reason need clarity and understanding in order to comprehend the fabric of nature, the forces bringing it to an end, and the consequence for humanity and the living world. Over the past centuries, humanity has assumed that nature is infinite, a free common good. If that assumption is wrong, reason tells us that the consequences will be severe and, for many of us, life-taking; emotion tells us that we may also lose beauty, and with it some of the substance of life itself. The debate is important and unresolved. To enter into it, we need to define nature, the challenges that may have ended it, and the future constructs that may replace it.

The statement that nature has ended begins with the idea of ''nature,'' but the scientific understanding of nature is still very limited. All modern science, physical and biological, is an investigation of nature, and the best known of all scientific journals is called, simply, *nature*. The vigor of our investigation hides much ignorance, as it is usually much easier to uncover detail than generality. By funding a professor to study a point mutation in a gene, or by setting a student to analyze the composition of a lava flow, society can reliably obtain results, but if we ask why the atmosphere is about one-fifth oxygen, not one-sixth or one-third, we will find no answer in the textbooks and very few scientific papers on the subject. Only brave young innocents or the bypassed elders of science dare to tackle a problem that is so poorly constrained. In consequence, we have no clear knowledge of the system that regulates the natural environment, the world about us, which to most people is ''nature.'' We understand weather fairly well, we have analyzed the air, we have counted the trees and classified the birds, but we do not yet fully know what deeper process regulates the composition of the air, the temperature of the planet, or the distribution of species.

Because our knowledge of nature is so poor, it is difficult to justify the proclamation of the end of nature. This point is often raised in the debate about the Earth: we cannot be certain about the death of what we did not know, and even if it has died, we should not mourn its passing. The human world is divorced from nature and the boardrooms of Tokyo or New York should not concern themselves with the fate of a distant ghost that may or may not have been destroyed by their actions. To this the rational answer is that the distant ghost may yet control the air of Manhattan; the emotional and more oblique answer is that the band on the Titanic also continued playing.

If nature has ended, that end has come swiftly. Today, as I write this during a visit to Cambridge, the college fellows play their lunchtime game of bowls on a soft green lawn, as they have done for centuries with the same ancient wooden balls. All, seemingly, is continuity, without termination or even change. The day is very warm for early February, and the spring flowers are opening. Above the buildings, flags stand out in the strong wind. There have been great storms recently, but perhaps this warmth and energy is part of the stochastic variability of weather, not evidence of permanent change. The flags fly to celebrate the anniversary of the accession of Queen Elizabeth II, a symbol of changeless continuity. Her accession took place in 1952, when nature seemed unchallenged: less than four decades later we debate nature's end. Just as the British Empire has vanished in those few decades, so also the wild empire of nature may have melted away. The elements of nature remain – we can breathe the air, rain falls from the sky – but power over the environment may have passed out of nature's hand. The spring flowers may not be opening at nature's call.

The old saying is that nature abhors a vacuum. If the power of nature has ended, then it is humanity that has become the regulator of the Earth's surface. In recent years, a continuing scientific debate, fostered especially by the American Geophysical Union, has considered the problem of nature's design, whether there are controlling laws that optimize the natural management of the environment. If there are no such laws, then all is accident and the death of old nature is simply another nasty accident, a loss of diversity but nothing seriously to perturb the body of humanity, though it may sadden our soul. If, however, there are laws that govern the stability of the environment, we need to discover them soon, so that we can manage the system after the death of our victim. It is also possible that nature is not yet dead, but has unknown laws and corrective mechanisms that will turn upon any destabilizing agent and remove it.

Humanity is disparate, in factions, and in rapidly increasing number. It is optimistic to assume that so divided an agent is able to replace the hand of nature, yet it is pessimistic to imagine that there will be no attempt.

In what follows, these themes – nature, its end, its replacement – are explored at length. Chapter 2 deals with the operation of the natural world, especially the atmosphere, and outlines some of what we know or suspect about the management of the planet. In Chapter 3 the forces that are causing change are discussed, with an assessment of the immediate consequences of change (Chapter 4), to discover whether or not they justify the reports of the death of nature. Chapters 5–7 examine the second part of the opening statement: if nature has ended, how shall it be replaced, and how is humanity to manage itself? Finally, the less rational but deeper aspects of the problem are briefly addressed: how should we live in a changed and still-changing world?

Reading list

Friday, L., and R. Laskey, eds. (1989). *The fragile environment: the Darwin College lectures*. Cambridge: Cambridge University Press.
McKibbin, B. (1990). *The end of nature*. New York: Viking Penguin.

2
The natural Earth

> But ask the animals and they will teach you, or the birds of the air, and they will tell you; or speak to the Earth, and it will teach you.
>
> Job 12: 7–8.

Stability is not natural, and there has never been such a thing as a perfectly stable natural environment. Throughout geological time the environment has been changing, sometimes slowly, sometimes dramatically. Life has adapted constantly to those changes; many of the changes were directly caused by life.

Humanity – modern *Homo sapiens* – evolved about 100,000 years ago, and immediately began altering the natural world. The effect seems to have been a wave of extinction of animals and plants: mammoths and mastodons, the lions of Judah and Greece, and the chestnuts of America. By the year A.D. 1950 the fauna and flora of the planet and hence the global environment were permanently changed, though not yet to the extent that climate was measurably altered.

2.1 The history of the natural Earth

The atmosphere regulates the temperature of the Earth's surface and has done so throughout geological time. Most models of the evolution of the Sun and solar system imply that the Sun was significantly fainter when it was young, billions of years ago, and has brightened over time. If these models are correct, the reason the early Earth did not freeze was that atmospheric gases acted as a warm blanket, increasing the surface temperature by as much as 50°C. Even today, with a bright Sun, the effective temperature of the Earth, which is the temperature of a hypothetical airless body that would radiate heat at the same rate as the Earth does, is well below freezing. A planet at this temperature would not support life. Fortunately the natural water vapor, together with carbon dioxide, methane, and other trace gases in the air, act to raise the temperature to a global average around 15°C, which is rather more comfortable. The gases blanket the Earth and keep the surface warm.

Nearly four billion years ago, the young Sun was probably only roughly three-fourths as bright as the modern Sun. Despite this, geological evidence shows that the oceans were liquid, because of the blanketing effect of the atmosphere which probably contained much more carbon dioxide (CO_2) than today. Scientists have little sure knowledge about the state of the early atmosphere; one suggestion is that it was dominantly carbon dioxide and nitrogen together with water vapor. At no time over the last four billion years is it likely that either methane (CH_4) or ammonia (NH_3) was a major component of the atmosphere, although trace amounts are sustained in the air by the emissions of living organisms. Sometime, probably in the period 4.2–3.8 billion years ago, life began on Earth. The oldest firm geological record of life dates from about 3.5 billion years ago, by which time there is evidence that a complex and varied bacterial community existed. Life had already started to use most of the important biochemical reactions, such as those involved in photosynthesis, and the geological evidence shows that life had begun to process the atmosphere, managing the oxygen and carbon dioxide, and nitrogen too.

For most of the Earth's history, life was single-celled and bacterial. Bacteria multiply to exploit all available resources, and so life was abundant, but left little fossil record. Around a billion years ago multicelled organisms evolved, and about 570 million years ago, at the beginning of the Cambrian period, the first animals with hard parts such as shells appeared. Over the next 100 million years the oceans were filled with a complex and competing chain of animal life. Colonization of the land began, first with simple plants, insects, snails, and so on. By the Permian and Triassic periods, roughly 200 million years ago, a complex ecological web had been set up on land, with a wide variety of animals and plants, and a diverse and complex community occupied the seas. Many of the larger Permo-Triassic land animals were mammal-like reptiles, including our own ancestors. During much of the Permo-Triassic time these mammal-like reptiles dominated the land. In the next two geological periods, however, it was not the mammals but the dinosaurs that became the largest and most numerous of the land vertebrates. Dinosaurs flourished and occupied much of the Earth. Then something happened: the dinosaurs suddenly disappeared at the end of the Cretaceous, about 60 million years ago.

Life is both fragile and versatile. It is fragile: at the end of the Permian in the seas, and again at the end of the Cretaceous on land and at sea, a diverse and seemingly stable ecosystem collapsed. The complex fabric of animal and plant life that previously had dominated the landscape and the seas disappeared. What-

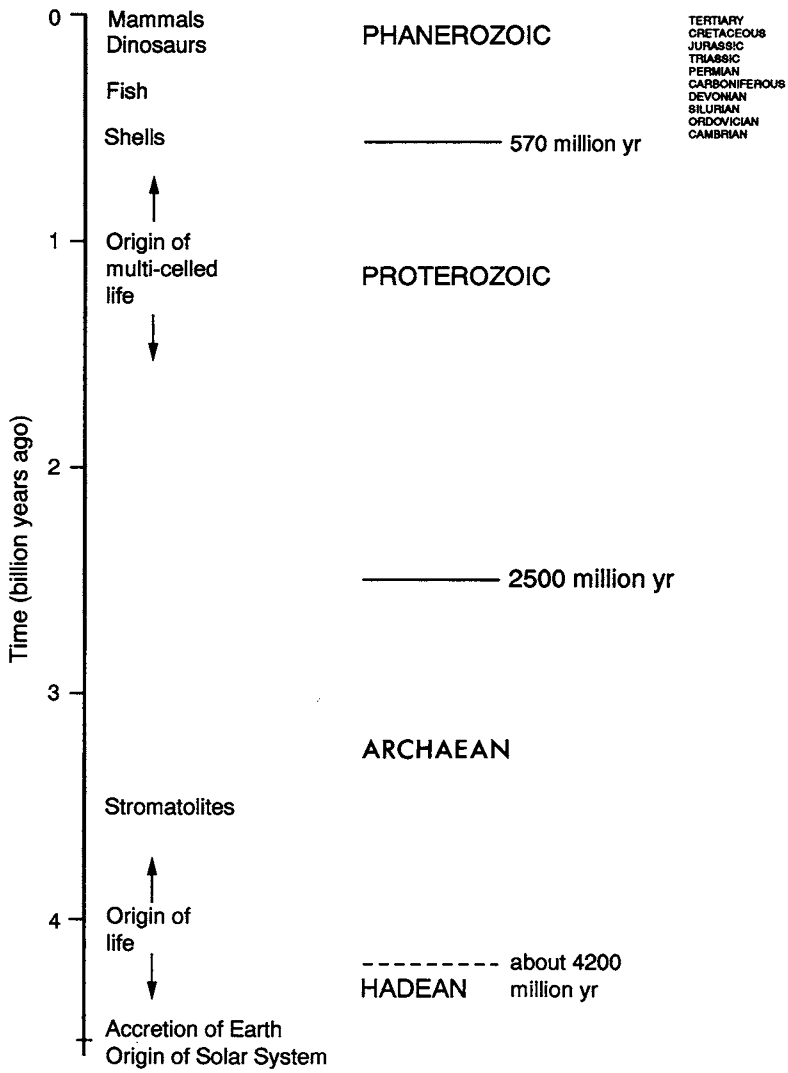

Figure 2.1. The geological time scale, showing the major events in the history of life. (Modified from Harland et al. 1989.)

ever the cause of the catastrophe at the end of the Cretaceous, when the dinosaurs died so did many of the plants. There is an extremely close relationship between life on Earth and the climate and atmosphere of the planet. The animals and vegetation changed, and so did the climate. Life is also versatile: the collapse at the end of the Cretaceous was followed by a period of ecological poverty, but then by further evolution to the richness and diversity inherited by humanity.

The interrelationship between climate and life has been recognized by a number of scientists, including the Russian V. I. Vernadski, who developed the notion of a *biosphere,* a term first made popular by the geologist E. Suess, to describe the realm in which life interacts pervasively with the environment. The biosphere is the thin skin on the Earth's surface in which life exists, varying from a few millimeters to a few hundred meters thick, though its influence pervades the planet. There is now some degree of consensus amongst atmospheric scientists that the biological controls exerted by the biosphere on climate are immense, pervasive, and critical. The composition of the air and the climate of the planet depend on life's history and present state.

The history of life on Earth, as deduced from the geological record, demonstrates that the biosphere is an extraordinarily complex interactive system which, like any human society, bears within itself the history and traditions of former times, and which can, on occasions, collapse disastrously. If enough links are broken, the whole fabric can unravel. This has happened several times in the past. Following each collapse, over the next tens of millions of years the fabric has been rewoven, but the community present at the time of the collapse never returns.

In the present century a large number of species has gone from the biosphere. This loss of species is equaled in the geological record only by the most massive extinction events, such as that at the end of the Cretaceous.

2.2 The physical controls on the environment

2.2.1 Energy

Virtually all the energy received by the atmosphere comes from the Sun. It is simple to show this: when one lies on a beach it is the sunny side of the body that is warmed. Some energy does come from the Earth's interior, but this contribution is small and is not normally important to the climate, except when volcanic eruptions change the reception of solar energy by placing dust and gas in the air.

The Sun is hot, and as a result the energy that arrives from the Sun comes as light characteristic of hot bodies, rich in radiation of short wavelengths, especially in that part of the spectrum which we can see with our eyes as the colors of the rainbow. The Earth returns to space an amount of energy equal to that which it receives from the Sun, to balance the incoming energy. If it did not, the temperature would climb steadily. Because the Earth is much cooler than the Sun, the energy emitted by the Earth is of much longer wavelength, in the infrared part of the spectrum. We cannot see this energy, but we can feel it as heat.

The temperature of the surface of the Earth depends on exactly how the balance of incoming and outgoing energy is achieved. On the natural Earth, some of the incoming solar radiation is sent straight back to space – either backscattered by air, reflected by clouds, or reflected directly from the surface. A larger fraction of the incoming radiation is absorbed by water vapor, dust, and gases such as ozone in the air, by clouds, and by the surface. The fate of this absorbed energy, especially the energy absorbed by the surface, controls the surface tem-

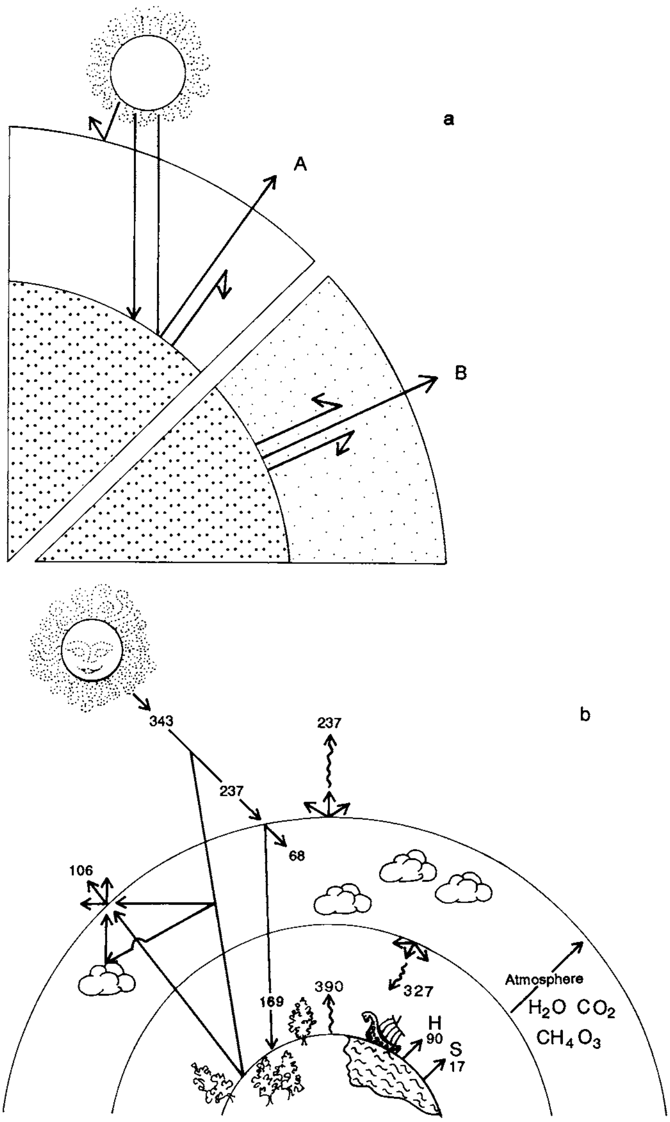

Figure 2.2. Energy inputs and outputs of the Earth and atmosphere. The diagrams show details of the complexity of the greenhouse effect. (a) An outline sketch of the greenhouse process. The greenhouse gases absorb the heat that leaves the Earth and reradiate it back to the surface, acting as a blanket. (The process is much more complex than this, as the lower diagram shows.) A: Sunlight falls on the planet and is absorbed or reflected at various stages as it penetrates the atmosphere. It is reradiated back into space at longer wavelengths. Some of this reradiated energy is absorbed by greenhouse gases in the air; if the concentration of greenhouse gases rises, as in B, more reradiated energy is absorbed in the lower atmosphere, causing temperatures there to rise before the energy is finally reradiated to space. (b) The global energy balance. Averaged over a year, the

peratures of the Earth. Some of the heat from the surface is directly radiated back to space, as infrared or heat radiation. Other heat is radiated from the surface to be absorbed by water vapor (in clouds or simply as vapor) and carbon dioxide in the air. Of the rest of the heat leaving the surface, part is carried up as heat that can be felt (e.g., in hot air), but much is carried in water vapor. An analogy is boiling a kettle: when we add energy, the water heats and then vaporizes into steam. It takes a large amount of energy to turn liquid water into vapor. This energy is then held in the vapor, and is called *latent heat*. On the Earth's surface, liquid water is vaporized and the vapor is carried into the air. As this happens, the heat is transferred from the surface into the latent heat in the water vapor in the air. We can feel the Sun's heat or the heat of a hot stone but we do not directly feel the heat carried up by water vapor (which is why it is called latent heat). The latent heat transfer is very important in controlling the surface temperature of much of the Earth's surface. The transfer of heat into water vapor happens all over the Earth, but especially over the tropical oceans. The rainforests also emit vast quantities of water vapor. To put it into physiological terms, it is as if the tropical parts of the Earth are sweating. Just as a human being sweats to keep cool on a hot day, so the forest emits water. J. E. Lovelock has used the term *geophysiology* to describe this process. There is a close analogy between the way in which we regulate our body temperatures, by sweating or by clothing and blankets, and the way in which the Earth operates.

2.2.2 *The greenhouse effect*

Some of the gases in the Earth's atmosphere play an especially important role in the energy balance of the planet because of the particular ways in which they absorb radiation. Some of these properties are shown in Figure 2.3. Ozone (O_3) is a strong absorber of light with a relatively short wavelength, in the ultraviolet. Carbon dioxide (CO_2) absorbs light at rather longer wavelengths, especially in the infrared region. Water has a complex absorption spectrum, absorbing light of various wavelengths. It also, of course, forms clouds. As light enters the atmosphere the energy is selectively absorbed by the atmosphere. Similarly, the

Caption to Figure 2.2 *(cont.)*
Sun's radiation brings 343 watts per square meter (Wm^{-2}) to the top of the atmosphere. For comparison, imagine all the output of three and a half typical 100-watt light bulbs shining on a square meter. Solar radiation amounting to 106 Wm^{-2} (or one light bulb per square meter) is reflected, which is why the Earth is a bright object to astronauts standing on the Moon. The other 237 Wm^{-2} are radiated back to space as long-wave or heat radiation, so that the planet is in radiative balance. The energy is processed in various ways as it descends to the surface and as it returns to space. The atmosphere absorbs some (68 Wm^{-2}). The surface receives 169 Wm^{-2} together with 327 Wm^{-2} of energy radiated down from the atmosphere to the surface. The surface radiates upward 390 Wm^{-2} of heat. The surface also gives off 90 Wm^{-2} of latent heat (H) and 17 Wm^{-2} of sensible heat (S). (Modified from Ramanathan 1988.)

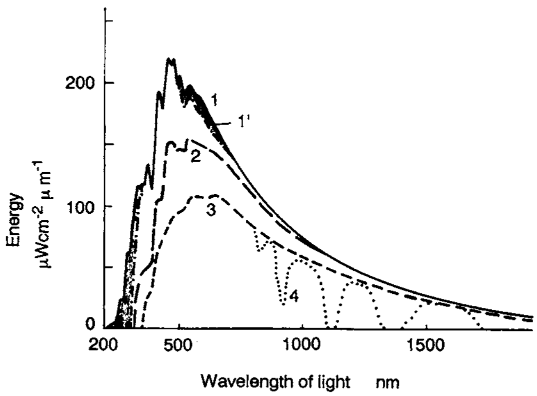

Figure 2.3. The passage of radiation from the Sun through the Earth's atmosphere. The horizontal axis is the wavelength, in nanometers, of the Sun's light, from ultraviolet (left-hand end), through the visible spectrum of the colors of the rainbow, to infrared (right-hand end). The vertical axis, in microwatts per square centimeter per micrometer of wavelength, is the flux of energy at each wavelength. Curve 1 shows the radiation arriving into the outermost atmosphere. Curve 1′ shows how much radiation emerges below the stratospheric shield of ozone. The shaded regions, especially around 200 to 300 nm wavelength in the ultraviolet part of the spectrum, indicate how much radiation is absorbed by the shield. The remaining radiation passes through the rest of the atmosphere, with further absorption and scattering by air molecules (Curve 2) and dust particles (Curve 3). Curve 4 shows the light that eventually reaches the Earth's surface, mostly in the region between 400 and 1000 nm. This region includes the visible spectrum, on which life depends and to which it is adapted. (From Deutscher Bundestag 1988, after earlier sources including Lacis and Hansen 1974.)

energy that is reradiated from the surface back into space is also selectively modified by atmospheric absorption as it passes through the air.

Sunlight that arrives at the top of the atmosphere is successively filtered by a variety of atmospheric gases and processes. The first major filter is absorption by oxygen and ozone in the high atmosphere (the *stratosphere*), which removes the energetic short-wavelength ultraviolet light. This energetic light is dangerous to most organisms, and so the ozone filter protects life on the surface below. As the light descends into the lower atmosphere, it is scattered by air molecules and chemicals in the air. The scattering process gives us a blue sky. In the lower atmosphere water vapor and other components of the air absorb light. This heats the air and reduces the intensity of the light that eventually reaches the surface.

In order to maintain a balance the Earth must return radiation to space. To expand the argument above, as much radiation must leave as enters. The temperature of the surface and of the various layers of the air depends on how this balance is achieved. A hot radiating body, such as the Sun, emits much short-wavelength light, such as ultraviolet light. This short-wavelength light is energetic. In contrast, a cool radiating body, such as the Earth, produces light of longer wavelength, in the infrared part of the spectrum, that is less energetic.