More Praise for *The Planet Remade*

"One of the most important and provocative books I've read in years. *The Planet Remade* is essential for policymakers, environmentalists, skeptics, and anyone else who prefers their views on climate change to be based on evidence rather than rhetoric."

—Hari Kunzru, author of *Gods without Men*

"Oliver Morton displays here again the usual virtues of his writing, which include a sparkling clarity maintained even when conveying huge complex masses of information, often about topics new to all of us; and then, even more importantly, good judgment. He makes distinctions when evaluating gnarly problems, and explains the distinctions very persuasively, and with a generous dry wit. All these abilities are now devoted to perhaps the crucial question of our time, the climate, making this simply a Necessary Book, which is also a pleasure to read. Maybe that combination makes it sui generis, but in any case it's an important addition to current discourse, an excellent way to get oriented to our most pressing environmental problem, and I urge people to read it and ponder its news."

—Kim Stanley Robinson, author of *Red Mars* and *Aurora*

"This is the first book to properly consider the dimensions of the new world we are living in. Morton's book is indispensable, highly readable, and incredibly timely."

—Mark Lynas, author of *The God Species*

"Written with the grace and clarity its subject demands, *The Planet Remade* offers just what the issue of climate change needs: fresh thinking about what can be done, based on deep respect for the planet, the science, and the concerns of people with differing points of view. It's an enriching addition to the literature of possible worlds."

—Marek Kohn, author of *A Reason for Everything* and *Turned Out Nice*

Oliver Morton

The Planet Remade

How Geoengineering Could Change the World

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Let us go then, you and I,
When the evening is spread out against the sky
Like a patient etherized upon a table

T. S. Eliot 'The Love Song of J. Alfred Prufrock' (1915)

In March of 2012, in a large-windowed conference hall on the snowy campus of the University of Calgary, I heard two simple questions. The man asking them was trying to help his audience get the most out of their day by giving them a clear understanding of where they, and others, stood when it came to action on climate change. To that end he asked them:

Do you believe the risks of climate change merit serious action aimed at lessening them?

Do you think that reducing an industrial economy's carbon-dioxide emissions to near zero is very hard?

Although this book is about more than climate change, it is because of the challenges of climate change that I have written it. And the two questions which were posed that morning by Robert Socolow, a physicist from Princeton University, seem to me a particularly good way of defining your position on the subject. So take a moment to answer them, if you would. The book's not going anywhere without you, and I think it will be a better read if you position yourself with respect to those questions before getting stuck in.

Here's a bit of context.

There is no serious doubt that the atmosphere's greenhouse effect is a key determinant of the Earth's temperature. Nor is there any serious doubt that carbon dioxide is a greenhouse gas, or that humans have been adding to the level of carbon dioxide in the atmosphere for the past few centuries by burning fossil fuels. In 1750, before the industrial revolution, the carbon-dioxide level was 280 parts per million. In 1950, when the great global boom of the second half of the twentieth century was taking off, it was about 310 parts per million. Today it is 400 parts per million. The bulk of that change has been due to the burning of fossil fuels. If you disbelieve any of those statements, you have been misled. I am not going to take the time to try and disabuse you in this book, and you should read on in expectation of frustration.

There is, however, a lot of room for doubt about the level of climate change the planet will see over the next decades and centuries. The best current estimate is that if fossil-fuel use continues on anything like current trends, the Earth is likely to end up at least two degrees Celsius warmer than it was before the industrial revolution, and possibly quite a lot warmer still. Change by one degree or two over a century or so may sound minimal, but it would be unprecedented in human history. Models of what happens to the climate in worlds in which fossil-fuel use is unconstrained point to severe, even cataclysmic, consequences in the form of damage to agriculture, greater harm done by extreme weather, the loss of biodiversity and sea-level rise over timescales of decades to centuries.

That said, different models provide different possible climates at any given carbon-dioxide level – some are more sensitive to the gas than others, in the language of modellers – and it hurricanes and volcanoes. Some people reject or denounce the implications of this change; others blithely accept them in a way that underplays their magnitude. I think those implications need to be opened up, inspected from different angles, interrogated, analysed, appreciated. Only then will it be possible to make the necessary judgements and choices.

Thinking about geoengineering is a worthwhile end in itself. But it is also an exercise in building up the imaginative capacity needed to take on board these deep changes the world is going through, and which it will continue to go through whether or not anyone ever actually attempts to re-engineer the climate. The planet has been remade, is being remade, will be remade. This book is an attempt to help people imagine the challenge those changes will bring.

Climate Risks and Responsibilities

Before going any further, though, let me justify my Yes/Yes. If you are already a Yes on either count, and impatient to boot, please feel free to skip ahead a section or two, as appropriate. If you are a No on one or the other count, let me see if I can bring you round, or at least clarify our disagreement.

First, the Yes as to risks from climate change that merit serious action. Some economic analysis suggests that there could be net benefits to the first degree or so of climate change, thanks to increased agricultural productivity in temperate zones, increased rainfall in some dry areas, less harm done by the cold at high latitudes and various other factors. If climate change due to carbon-dioxide emissions is a net benefit to the world, some people argue, countries should take no concerted action against it.

But in no such projections is everyone better off. And those who end up worse off are for the most part the people who start off poorer and who are responsible for fewer carbon-dioxide emissions, such as farmers and the urban poor in developing countries. I think that if carbon emissions do harm to those unfortunates, then people in rich countries and rich people in poor countries – the two groups, each about a billion strong, whose ways of life account for an overwhelming share of emissions – have a duty to act. That duty persists even if the emissions are somehow helping other people, such as rich-world farmers or old people at risk of death in cold winters. In most peoples' moral systems, you do not get a free pass to do harm to one set of people just because you are doing good to another set.

I understand that cutting emissions is by no means the easiest way to help the people whom those emissions put at risk. Easier immigration to rich countries; well-implemented development aid; political reform that puts more weight on the livelihoods of the poor; a more open trade system: all these policies offer more immediate solutions. But helping in those ways, while admirable and a good idea regardless of what else is done, would not fully excuse the climate harm. Just as it is wrong to help some people with one hand while hurting others with the other, you can't knock people down with impunity just because you are willing to slip them some cash first and pick them up off the floor afterwards.

Not everyone will accept this reasoning, and some who do accept it will, as a matter of pragmatism, feel justified in settling for net good even when it involves harm to some vulnerable people. But there are other reasons for believing that climate change merits a serious response. Climate change may be neither as big a problem nor as poorly tolerated as most of those who study it think; but even were this the case, there would remain a fair chance that it will be pretty bad, and a smaller chance that it will be very bad indeed. Let's say there is a 50 per cent chance of net harm, and a 5 per cent chance of this harm being very severe. To me, those odds justify serious action. A 5 per cent chance is one in twenty: pretty close to the odds that, on throwing a pair of dice, you will get either a double six or snake eyes. Not likely, but a long way from unheard of. When I was told on reasonable authority that my risks of a cardiac event in the next fifteen years or so were about 6 per cent, I resolved to make some changes in the way I lived my life. A little later I actually managed to act on those resolutions.

A straightforward reading of the latest assessment by the scientists of the Intergovernmental Panel on Climate Change (IPCC) would suggest that the risks are higher than those I just gave; many scientists and almost all environmental activists would put them much higher. But if you think, as I do, that figures as low as 50 per cent and 5 per cent justify action, it doesn't really matter for the purposes of this discussion if the figures are actually higher. Provided that threats to the world at large move you, you have already bought into the case for finding a way to act.

If you require more specific threats – threats to yourself, your loved ones, your descendants and theirs – things are not so clear-cut. I will not pretend that climate-change risks are all that high for reasonably well-to-do people in developed countries in the next half-century or so, and I imagine that describes most of my readers. My choice to worry about the more general threat is, I recognise, a choice. You may choose differently.

So those are my reasons for a Yes to the first question. What about those of you who answered No? Some, as mentioned, may find threats to humanity at large insufficiently motivating. Among the others, there seem to me to be two ways you might have come to your No. You may think that my one-in-twenty chance of catastrophe is small enough to live with. Alternatively, you may think that a 5 per cent chance would indeed justify serious attempts at risk reduction, but that the odds are actually longer than that – that the chance of catastrophic harm is, say, one in a hundred.

In the first case, the one where you are less risk-averse than I, there's probably not much I can do to change your mind. Please read on, though. I hope that readers do not have to agree with all the premises of this book to find its ideas stimulating and its effect on their imagination rewarding. I also suspect that some of those ideas are going to sound disturbingly risky to many readers. It will be nice to have a few people who laugh in the face of danger come along for the ride.

In the second case, the one where you think the risks are less than one in a hundred, I think you are displaying an indefensible level of certainty about how the climate works and how much carbon dioxide will be emitted over the next century. I can see that it would be nice to feel that level of certainty. But I just don't see how you can if you've looked at the issue seriously. Given the uncertainties involved, to be sure that a climate disaster is that unlikely shows a self-confidence so well developed as to be indistinguishable from folly.

The Second Fossil-Fuel Century

What about the other Yes? Why should moving off fossil fuels be so difficult? The answer lies in the scale of the problem and the speed of the change required, and – fair warning – it will take me rather longer to run through than the first Yes did.

The 30 billion tonnes of carbon dioxide emitted in 2013 came from burning three trillion cubic metres of gas over the year; from burning almost three billion barrels of oil in each of its months; from burning a bit less than 300 tonnes of coal in each of its seconds. The infrastructure needed for all that burning was almost as complex as it was essential.

To stabilize the climate by means of emissions reduction means replacing the whole lot.

The world has made huge investments in the facilities that extract fossil fuels from the ground and burn them – mines, oil wells, power stations, hundreds of thousands of ships and aircraft, a billion motor vehicles. Leaving aside the political lobbying power that such investment can command, there would be a limit to how quickly that much kit could be replaced even if there were perfect substitute technologies to hand that simply needed scaling up. If the world had the capacity to deliver one of the largest nuclear power plants ever built once a week, week in and week out, it would take 20 years to replace the current stock of coal-fired plants (at present, the world builds about three or four nuclear power plants a year, and retires old ones almost as quickly). To replace those coal plants with solar panels at the rate such panels were installed in 2013 would take about a century and a half. That is all before starting on replacing the gas and the oil, the cars, the furnaces and the ships.

And the challenge of decarbonization is not just a matter of replacing today's extraordinary planet-spanning energy infrastructure; you have to replace the yet larger system it is quickly growing into. The twentieth century began with a world population of 1.6 billion, none of whom enjoyed the energy-intense affluence of the citizens of today's modern industrialized states. Today's emissions are for the most part a result of the fact that two billion people now lead such lives.

But there are five billion more people in the poorer countries not leading such lives. About a quarter of those people lead lives illuminated only by sun, moon and fire, with no reliable access to modern energy supplies of any sort. They deserve better. All of those people should be able to lead the lives that the affluent two billion lead today, with access to the industrial and agricultural goods and services that copious energy makes possible. And so should their children and grandchildren.

The world's population is expected to grow from seven billion today to more or less ten billion by 2100. By that time the number of people enjoying rich-world energy privileges should also reach ten billion. So the challenge is to achieve for an extra eight billion people in the twenty-first century what was achieved for two billion in the twentieth century. Meeting that challenge implies a lot more energy use. It may be that a solar power have been deployed on an industrial scale for the first time. There are now single installations with a capacity of between 100 megawatts and a gigawatt – facilities similar in size to advanced gas-turbine plants at the bottom end and nuclear plants at the top end.

(A note here on power and energy: power is the rate at which energy is made available or used over time; it is measured in watts, and multiples of watts. A human body burns up the energy in food at a rate of about 100 watts. The 1.5-litre engine in a compact car like a Toyota Corolla generates power from gasoline at about 50,000 watts, or 50 kilowatts (50kW). A really big wind turbine turns the energy of the wind into electricity at a rate of 5,000,000 watts, or five megawatts (5MW). A big power station typically runs at a billion watts or so – a gigawatt. The energy use of a major economy like America's, Europe's or China's is a thousand times larger still: something like a trillion watts, which is a terawatt (1TW). Energy is what you get if you multiply power by time. Use a kilowatt of power for an hour, and you have used a kilowatt hour.)

The attraction of renewables goes beyond drastically reduced greenhouse-gas emissions. Burning fossil fuels produces a wide range of 'aerosols' – tiny particles floating in the atmosphere (aerosol spray cans are so called because they turn their contents into such particles). Millions of lives are shortened each year because of the harm these aerosols do when inhaled; power plants that burn coal are particularly grievous offenders. Chemical contaminants created by generators and engines – nitrogen oxides and ozone – also do a lot of damage, both to people and to crops. And the supply of fossil fuels can fluctuate wildly, either because of changes in the market or because of politics. The fuel costs for some renewables, on the other hand, are fixed and very low – wind, sunshine and the tendency of water to flow downhill come for free, and the plants grown to burn as biomass can often be furnished pretty cheaply, too.

It is a fine list of benefits. But there is a second lesson from Grübler's studies of past energy transitions to be confronted. They have, in the main, been driven not by the availability of new ways of providing energy, but by new ways of using it: transitions are pulled by demand, not pushed by supply. Electricity and internal combustion engines were adopted because they allowed people to do things they hadn't done before, and people demanded those new energy services in ever-greater numbers. The requisite fuel supplies, generating technologies and distribution systems raced to catch up. There is simply no precedent for a wholesale change that doesn't offer users appealing new possibilities in terms of the way they use the energy – for a change that is pushed through rather than pulled along. And as far as the end user is concerned, renewable electricity is just another form of electricity – it offers no advantage as a means of powering things, even if generating the electricity that way has various charms. Its benefits are felt at the level of the system, not at the level of the individual buyer. That means a renewable-energy transition will need significant pushing.

As with Grübler's observations about the time transitions take, this points merely to decarbonization being unprecedented, not impossible. But the best example in recent history of an energy transition that governments tried to push through, rather than simply letting users pull, is not very encouraging. Governments in various countries pushed quite hard for a transition to nuclear power in the 1960s and 1970s. In many of them, though, the technology's early growth subsequently stalled.

This was in part an economic matter. In America, in particular, early promises of cheap and plentiful power failed to pay off as companies saw the costs of nuclear plants go through the roof at the same time as the growth in demand they had expected failed to materialize. But on top of this, the 1970s saw a catastrophic turn in the way people thought of and talked about the future; nuclear power played a role in this turn, and suffered from the consequences of it. I think it is worth looking at that process in a little detail, not just because of what it says about energy transitions, but because it throws light on our main themes. As will become apparent at various times in the course of this book, little else can hold a candle to the energies of the nucleus when it comes to imagining the impacts of world-changing technology.

In its early years nuclear power benefited from a carefully crafted position as the epitome of the scientific progress taking the world forward into a better future. Although there was a persistent undercurrent of cold-war anxiety, there was a general enthusiasm for the future that nuclear power was held to offer. Initial concern about nuclear power imagined it posing an insidious and ubiquitous threat, contaminating the world through its very existence in rather the same way that nuclear fallout did. It was neither a plausible concern nor one that gained much traction. Many environmentalists focused instead on the technology's environmental benefits; in terms of cleaning up the air people breathed nuclear plants promised to be a great step forward from coal plants.

In the 1970s, though, the original fear of nuclear business-as-usual was at first reinforced, and then displaced, by a fear of nuclear accidents. The notion of the meltdown focused nuclear anxiety on specific events, and relied on increasingly widespread concerns about the military-industrial complex and the technocratic hubris of governments. At the same time, it maintained the underlying sense of an invisible, intangible and global threat that makes all concerns about radiation so unsettling and prone to irrational exaggeration. The double vision in which specific accidents were also global threats reflected the sheer scope of the effects imagined: a ball of radioactive slag produced in a meltdown passing right through the Earth (the 'China Syndrome'); a meltdown poisoning its surroundings for geological periods of time. On top of these fears about what would happen if the nuclear-bomb-like energy of a reactor got out of control were worries about the levels of control that organs of state security might impose on the public to stop any saboteurs seeking to bring about disaster. The power needed to keep the genie bottled up was as worrying, to some, as the power of the genie unleashed – maybe more.

The new nuclear fear was not the only factor behind the stall in the transition to nuclear energy. In America, as noted, the technology proved to be far more expensive than its proponents had hoped, in part because of the rushed way in which it was rolled out. By the time of the Three Mile Island accident of 1979, which did a great deal to cement anti-nuclear fears in the American imagination, no new nuclear power plants had been ordered in America for more than three years. But the new fears added to nuclear power's woes, and indeed its costs, by making permission to build plants harder to gain; the current mixture of expense and public disquiet goes a long way to explaining why most nations with nuclear-power programmes get less than 20 per cent of their electricity from them and have expanded them little since the 1980s. (The great exception is France, which has a culture of technocratic planning, a trust of engineers on the part of both the public and the policy-making elite, a history of valuing its energy self-sufficiency, governments consistently happy to take a direct role in running the energy system and low fossil-fuel reserves. Nuclear reactors generate almost 80 per cent of its electricity.)

There are now environmentalists who would like to shock the stalled nuclear transition back to life as a way of fighting climate change. They argue that nuclear power's obvious problems – the risk of accidents, the production of radioactive waste and the facilitation of bomb building – are nothing like as bad as they have been painted, and pale compared to the damage climate change could do, and they are mostly right.

Only one nuclear accident – that at Chernobyl, in 1986 – has led to significant loss of life. Current assessments of the Fukushima meltdown suggest that there will be no discernible deaths as a result. Compare that with more than a million who die with coal-ruined lungs every year. New nuclear reactors built to the standards demanded by experienced government regulators with the power to have their decisions respected will be significantly safer than older designs. Long-term storage of waste has been politically mismanaged in many countries but is neither a particularly pressing problem – safe interim storage solutions that can last for decades, even a century, are tried and tested – nor a fundamentally intractable one. Though many civilian nuclear-power programmes have been linked to weapons development, those links have often proved breakable: neither Argentina nor Brazil is currently pursuing a bomb; South Africa gave its bombs up. Proliferation is a grave risk, but doing without nuclear electricity would not lead to a proliferation-free world. North Korea and Israel have produced nuclear weapons with no civilian power programme at all.

Despite all this, there seems little likelihood either that the green movement will pivot to nuclear power en masse or that the number of reactors will grow substantially. They remain more expensive watt-for-watt than fossil-fuel plants, most hydroelectric dams and some wind installations, and they only come in large sizes, which means you have to buy a billion watts or so at a time at costs of tens of billions of dollars. While smaller reactors would alleviate some of that problem, their development is difficult – nuclear power is, given the items involved and the regulations that surround them, a hard area in which to innovate. And nuclear energy enjoys none of the demand-pull that was crucial to earlier energy transitions; for a domestic or industrial user, nuclear electricity is no better than any other sort.*

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* This is true for civilian power; in the military, however, nuclear electricity does have a key advantage, in that it can be used to power submarines which would otherwise have to take on air through a snorkel so that they could burn diesel. It was this small but crucial niche that led to nuclear reactors capable of generating electricity being developed in the first place.

long run both rise and become more volatile. At the time of the Copenhagen summit it was argued that if Europe were to become a renewables superpower it could avoid those costs and get ahead of the rest of the world.

But fossil fuels have become cheaper, not more expensive, and look likely to stay quite affordable for rich countries for decades to come. Attempts to make fossil-fuel prices higher through carbon taxes and similar schemes could, in principle, change this, forcing a lot of investment into alternatives. But in most places they have not attracted enough political support to stick, and it is not clear that they can. They would stand a better chance in a world that coordinated its actions internationally; when people talk about the low costs of a transition to renewables, they are imagining it taking place in such an optimal world. But that world has not yet been achieved.

Instead of increasing the costs of fossil-fuel generation through a carbon price or tax, governments have preferred to subsidize renewables. One problem with this is that it doesn't encourage people to stop using fossil fuels in existing plants; it just rewards people for building alternatives. Another problem is that the more renewables get built, the pricier the subsidies get. Germany's current *Energiewende*, a national policy which aims to cut carbon-dioxide emissions from the power sector drastically while at the same time retiring all of the country's nuclear plants, seems set to find out how far such subsidy approaches can go; they have cost well over 100 billion euros to date. In general, few economies have wind, solar or biomass supplying much more than 20 per cent of their electricity market (the same sort of level, possibly coincidentally, that has been achieved in the other push-not-pull attempt at an energy transition – that of nuclear power). That's a large enough fraction to transfer a significant amount of money to the builders and buyers of wind turbines and solar. But it is not enough to change the course of the planet's climate.

This reflects a general issue with environmental policies;

they are often aimed at pleasing voters and lobbies with green interests more than they are geared to achieving the stated environmental ends. People see wind turbines being built in prodigious numbers, and see solar cells on roofs, and think they are looking at a solution. In fact, in part because of the low energy-density of renewable energy, these impressive – and, to some, infuriating – sights are achieving very little in terms of providing enough power for a world of ten billion reasonably well-off people.

Renewable efforts do not have to be paltry. The *Energiewende* is no small thing. And it is possible that Germany – a rich, technologically potent country which is rather good at sustaining national consensus – may be able to convert itself almost entirely to renewable energy. That said, in 2013 Jane Long, formerly the associate director for energy and the environment at Lawrence Livermore National Laboratory in California, chaired a study of the prospects for emissions reduction in her state – also rich and technologically potent, though less adept when it comes to political consensus. Long's study found that by encouraging energy efficiency, completely replacing fossil fuels as a source of electricity and greatly reducing their use in industry and transportation, California might cut its emissions by 60 per cent over 40 years. With a justifiable pride in her home state's record on innovation and commitment to environmentalism, Long says that if California can't do better than that, no one else can. And compared with that scenario, which made use of nuclear power as well as copious renewables, Germany is aiming for a higher target with one arm tied behind its back.

But the challenge of decarbonization would not be met just by a few environmentally conscious economies cutting their emissions by 60 per cent, or 80 per cent, even if they could; all the big emitters need to get on paths that take them to 100 per cent if the level of greenhouse gas in the atmosphere is to be stabilized in this century, with the electricity sector carbon free a lot earlier. Just half of them doing so does not cut it – and perversely, by reducing demand, it might well reduce the cost of fossil fuels to the other half.

It was the fact that all the big emitters need to be involved that drove the hoopla over Copenhagen. But the belief that the world can in some way come together to agree to do as a whole what its large economies are not obviously willing to do individually is illusory. There is a value in international negotiations: they can help shore up a sense of purpose; they can provide something by way of sticks and carrots. But an international agreement will not lead any government to follow climate policies that are clearly not supported at home for reasons of ideology, cost, or any other factor. And an international agreement on climate questions is also peculiarly hard to come by.

There are many reasons why this is so, most of them linked to the fact that the people who do most of the emitting do not face most of the risks from climate change, and also to the fear that if some act but not all, then those who do not act will get as much of the benefit as those who do. Most crucial of all, though, is the problem that whatever benefits there are and to whomever they accrue, they will not be felt for decades. The climate depends on the cumulative carbon emissions – on the total stock that has been added to the atmosphere over centuries, not on the rate at which they are added at any particular time. Any plausible cuts in carbon-dioxide emissions made today would have more or less no effect until the mid-century. By that time the costs of inaction might be horribly plain – but there will be no time machine with which to come back and set the necessary cuts in motion on the basis of that future knowledge. As Hans Joachim Schellnhuber, an influential expert on climate-change impacts, puts it, 'climate change is too slow a problem to solve in time'.

The costs of action and the lack of an international mechanism do not mean there will be no decarbonization in the decades to come; but I suspect it will be more like that seen in China than on the scale imagined in Germany or California. China is building more renewable capacity than any other nation, and is ramping up a big nuclear programme, too. It is also enacting ambitious energy-efficiency measures. But this is only slowly reducing the proportion of its energy it gets from fossil-fuel use. Its current plans have its carbon-dioxide emissions continuing to rise until 2030 – at which point 80 per cent of Chinese energy will still be coming from fossil fuels. How quickly it might fall after that is anyone's guess.

As China, so the world. An investment in non-fossil-fuel sources of energy great enough simply to keep up with increasing demand is a huge commitment. An investment big enough to displace fossil fuels entirely does not look to be remotely on the cards under current conditions. Between 1750 and 2000 humans released half a trillion tonnes of the carbon that the Earth had stored up in fossil fuels. It is very hard to believe that, over the coming century, they will not release a trillion tonnes more.

Altering the Earthsystem

Yes/Yes is compelling to me, and I hope it now looks pretty reasonable to you. But as Rob Socolow pointed out in that big-windowed Calgary hall, it is a minority view.

Those who oppose climate action sit firmly in the No/Yes camp. For some of them, the Yes drives the No. If you understand that, Yes, action on fossil fuels is hard – hard technically and hard on people who get hit with higher electricity and fuel bills, as well as hard on people who have investments in oil, gas and coal – concluding that No, it isn't necessary is quite convenient. People in the No/Yes camp have a fair bit of motivation to search for reasons to doubt the science behind calls for action, a search with which organized lobbies have been happy to help.

The Yes/No camp saves its doubt for people who point out the impracticality of an energy transition on the scale required to make a big change in the risks. Politicians who accept the need for climate action insist that it will be relatively painless, maybe even an enjoyable improvement, bringing jobs and growth. The greens who accept that sharp reductions in fossil-fuel use will indeed have costs often imagine them falling predominantly on big businesses. Some also argue that the costs are, in a way, illusory. While less affordable energy and consequent drops in consumption look like a 'cost' to economists, some greens see the latter, in particular, as a benefit.

The rich world contains quite a few people who have found that they can lead happier lives with less stuff, and the same might be true of many more, if we could only see our way to making that choice (I say 'we' here because I accept that I may be among those who, because of the ingrained mindset of consumerism, are failing to follow a course of action which might make them happier). But as Pat Mooney of the Canadian environmental group ETC (it stands for Erosion, Technology and Concentration, and is pronounced 'et cetera') pointed out to me a few years ago, people who see some evidence that choosing a path of lowered consumption would make them happier and yet do not choose to act on that evidence are very unlikely to make the same choice for the benefit of others. And it is also unlikely that they will acquiesce in being forced down the path of happiness unchosen. 'Lead the life I want you to lead or the planet gets it' is not only an unattractive position, it is an ineffective one.

The world's political leaders are resolutely Yes/No or No/Yes, and most of the public seems OK with that. But the people Socolow was addressing in Calgary had pretty much declared for Yes/Yes simply by turning up. If they had not both taken responding to the risks of climate change seriously and believed fossil fuels were hard to get rid of they would not have bothered to attend a meeting on innovative chemical-engineering techniques for pulling carbon dioxide out of the air, a technology known in climate-change circles as 'direct-air capture'. Used

When the change that humans bring to this new Anthropocene state of the earthsystem is deliberate, I see it as geoengineering; in this book, that term will cover any deliberate technological intervention in the earthsystem on a global scale, not just those aimed at countering, or ameliorating, the changes that people are making to the climate without deliberation. The notion of deliberation matters; to the earthsystem, a change made in passing may be no different to one made on purpose, but in the human world there is a difference between the changes you make and those that you plan, between having an effect on the future that you can foresee and having an effect that you intend. The extinction of the dodo is one thing; that of smallpox is another.

The effects of piling more and more carbon dioxide into the atmosphere can be foreseen, though not in as much detail as one might like. But they are not exactly intended. If the effects were to be reduced by machines capable of sucking carbon dioxide out of the atmosphere, like those under discussion in Calgary that morning, the resultant change would be intended, even if not all its impacts could necessarily be foreseen. Thus large-scale direct-air capture of carbon dioxide would be a way of giving the Earth a climate other than the one it would expect, given the amount of carbon dioxide that human activities have emitted. And that is what climate geoengineering aspires to more generally. Climate geoengineering can be pursued in very different ways, but the aim is always to decouple the climate from humanity's cumulative emissions of carbon dioxide. It is to unshackle, if only to a very limited extent, the future from the past.

Deliberate Planets, Imagined Worlds

If direct-air carbon-dioxide capture of some sort could be implemented safely on an arbitrarily large scale it is hard to imagine that it wouldn't be. Sucking carbon dioxide out of the atmosphere as fast as it was pumped in would seem to more or less solve the climate problem, as long as somewhere could be found to put the carbon dioxide thus sucked out. Maybe it could be stored in reservoirs underground; maybe it could be turned into solid carbonate rock; maybe it could be turned back into hydrocarbon fuel, so that such fuels would never run out.

Unfortunately, at the moment direct-air capture cannot be implemented on a remotely large enough scale because there is no proven technology for taking carbon dioxide out of the air that is practically or economically up to the job. And if your goal is to pull carbon dioxide out of the atmosphere at anything like the rate at which it is currently being pumped in, it's a very good bet that no such technology will ever exist. Some of the reasons why this is the case – as well as the promise direct-air capture might still offer while never meeting such an all-encompassing goal – will be discussed later. What I want to bring to your attention here is not the detail of the technology, but something about the people trying to make it real.

There were four groups actively working on the idea at the Calgary conference, and three of them had something striking in common. They were all fronted by charismatic North American physicists, the sort of people who impress and inspire students by showing the near-inexhaustible ability of physics to provide answers, and by encouraging them to ask questions to which the answers are truly interesting. They are the sort of men who make knowledge – both theirs and, once you learn from them, yours – feel like power. Men of human empire.

They are also the sort of men who can attract the interest and admiration of wealthier and more powerful men. All three of the physicists whose work was under discussion in Calgary were professors at prestigious universities, but their air-capture work has been mostly done under the aegis of companies they started for this purpose with the help of investments by rich sponsors. Klaus Lackner, of Columbia University, the first person to make a splash working on direct-air capture, was able to take his ideas about 'artificial trees' forward thanks to the backing of the late Gary Comer, the man who founded Lands' End clothing; Peter Eisenberger, also of Columbia, who dreams of using solar power to turn the carbon dioxide captured from the air back into fuel, attracted Edgar Bronfman of Seagram. David Keith, then at the University of Calgary and now at Harvard, landed the biggest fish of all. The main investor in his direct-air-capture company, Carbon Engineering, is Bill Gates.

To some, this will seem proof enough that climate geo-engineering is a pernicious capitalist plot. Further proof, if needed, might be adduced from Richard Branson's enthusiasm for such schemes (he has set up a prize to reward progress in pulling carbon-dioxide from the atmosphere). When Branson said, in 2009, 'if we could come up with a geoengineering answer . . . then Copenhagen wouldn't be necessary. We could carry on flying our planes and driving our cars' you could all but hear green hackles rise at such get-out-of-jail-free sentiments from an owner of airlines. But if it is all a plutocrats' plot, it is a very poorly contrived one. The Calgary meeting had been arranged by Keith to discuss the cost of the schemes in question. A report by a panel of the American Physical Society, chaired by Socolow, who has a long background in energy and climate studies, had derived costs for capturing carbon dioxide from the air of around $600 a tonne, possibly much more. That was far higher than the figures Eisenberger and Lackner had floated, and more than double the less ambitious figures Keith's company talked about. The meeting was intended to thrash out the differences.

It managed to get some way towards that goal; members of Socolow's panel admitted that their estimate might be slightly high, though they didn't think that would make any difference to the technology's feasibility. Keith still thinks that they are wrong, and that it is conceivable that his direct-air-capture technology might turn a profit in places where there is an industrial need for more carbon dioxide than can easily be brought in on trucks and where, in addition, the government has set a significant price on carbon. But he is talking tens of thousands of tonnes, not tens of billions. No one could have come away from Calgary thinking that direct-air capture was anywhere close to being a viable tool for large-scale climate geoengineering. Anyone investing in direct-air capture as part of a plot to take over the climate is making a mistake.

If, then, direct-air capture doesn't really matter, why think about it? Because it may matter, in time – and because knowing that helps put the present into context and lets you imagine the future more fully.

In the Yes/No and No/Yes camps, the details of the future don't much matter. The fear of bad outcomes motivates both climate activists and their foes, but the precise details don't matter. Both sides see themselves as averting a future that they don't like more than creating one that they do.

The Yes/Yes position requires a richer imagination – one that allows that the future may be quite different. It is in the Yes/Yes world that you will find people who are open about the need they see to fundamentally change the world economy so that it no longer demands or delivers constant growth – an option today's liberal democracies, even green-looking ones like Germany, scarcely countenance – or to return large numbers of people to a relationship with nature centred on the land. It is in the Yes/Yes world that you will find people who think, with regret but with clear eyes, that more or less all that can be done about the risks of climate change is to equip the afflicted with the means to ride those risks out, and that even then adaptation may be beyond the reach of billions. It is in the Yes/Yes world that you will find the most plaintive Cassandras, convinced that catastrophe is now inevitable.

And it is in the Yes/Yes world that you will find people imagining a planet where the earthsystem is manipulated in such a way that climate and carbon emissions are no longer so tightly bound. There is much to criticize in such thinking. It can be horribly simplistic. It can feed on, and give rise to, ideas about 'the control of nature' that are neither plausible nor palatable. It can be used to justify inaction. But I believe it can also open up doors, doors both practical and utopian. I think there may be ways in which climate geoengineering could really reduce harm. I also think that imagining geoengineered worlds that might be good to live in, in which people could be safer and happier than they would otherwise be, is worth doing. A utopia does not need to be attainable – indeed, by definition it cannot be. But that is not a reason to reject utopian thought. It is part of the reason for embracing it.

The possibilities of utopian imagination, though, are undercut, even betrayed, if the group doing the imagining is too small. That is currently the case, I think, for geoengineering. Listen to the discussion of the topic going on today and you will hear natural scientists who are cautiously curious about the ideas but have no real interest in trying to make them practical; you will hear social scientists and philosophers interested in providing critiques of the modes of thinking that shape the discourse; you will hear environmentalists who see in it, or project on to it, everything they dislike about centralized action, about capitalism, about mechanistic world views; you will hear the fantasies of the rich and powerful and the fears of the frightened and doctrinaire. It is too small a set of voices.

The way a society imagines its future matters. And who gets to do the imagining matters. The purpose of this book is to spread the tools with which to imagine a re-engineered earth-system a little more broadly. In doing so, it looks at the scientific possibilities under discussion. It also looks at the history of that discussion, at the beliefs people have held about the proper relationship between climate and humanity, at the political contexts that have grown up around those beliefs. I fear that may make it sound like the driest sort of imagining. I hope it

PART ONE
Energies

1

The Top of the World

One might say that immensity is a philosophical category of daydream. Daydream undoubtedly feeds on all kinds of sights, but through a sort of natural inclination, it contemplates grandeur. And this contemplation produces an attitude that is so special, an inner state so unlike any other, that the daydream transports the dreamer outside the immediate world to a world that has the mark of infinity

Gaston Bachelard,
The Poetics of Space (1958)

The sun is shining, but the sky above is Bible black. It takes on colour only lower down, first deep violet, then, just above the encircling horizon, a band of blue and white. The descending, brightening sweep of colour gives a swelling curve to the sky.

Within that encompassing blue-white band, the bright-below Earth, too, is curved. It bends away in every direction towards its blue-lipped rim.

The only straight line in this whole vast, round, empty world is the wing.

You are 22 kilometres up, well inside the stratosphere – a realm which, although it is about as peripheral as a part of the Earth can be, plays a central role in the story to come. If climate geoengineering ever takes place, there is a good chance that it will take place up here, in the Earth's attic. If it does not take place, it may well be for fear of the damage it could do to this bright-lit void.

Even if it were not a crucial locale for geoengineering schemes, though, the stratosphere would still have much to recommend it as the starting point for a book about the environment, its protection and its politics. Its short history – it was discovered only in 1902 – weaves together threads of scientific exploration, military ambition and environmental concern. Beyond that, though, in its liminal way the stratosphere seems to me a perfect setting in which to begin a book which looks at the way the earthsystem works and ways it might work differently, a book about the boundaries between physical planets and imagined worlds.

You are an inhabitant of the Earth's surface who has, in all likelihood, seen more of that surface than your ancestors would have dreamed possible; you are probably the sort of person who can imagine crossing an ocean for a holiday: and so you think that you know the Earth. But less than a day's walk vertically above you, your planet offers an environment beyond your ken, a realm without local features or breathable air, a windy but oddly weatherless stack of atmospheric layers sliding around from equator to pole without storms or clouds. The rules that govern the workings of the lower atmosphere are turned on their head up here, and common-sense ideas about the world you have picked up on its surface hold no sway. In understanding the world below, science can feel like an optional extra. Here it is indispensable.

The stratosphere is closed – a volume of about 15 billion cubic kilometres with well-defined boundaries at its base and at its top. At the same time as being finite, though, it is all-encompassing – no bit of the world below lacks a stratosphere above, no trip beyond the world can avoid passing through it. In this, it is a realm not simply described by science, but oddly akin to science itself: limited but all-encompassing. Like the stratosphere, science is, in its way, alien to everyone; it is at the same time, and by the same measure, common to all, sheltering the just and unjust alike. It provides a viewpoint from which the world is bigger and stranger than it seems from the surface. The world thus revealed is more abstract, too, and there is no denying that something is lost in that. Yet a sort of universality is gained, and a liberating rootlessness.

I prize that rootlessness. I also worry about it. That is why, in our thinking, I would not have our scientifically informed imaginations waltz around this vast curving ballroom completely unconstrained, like dancing giants of the mind. That is why I insist, as you look out to the blue-white-bright horizon, that you also see the wing, straight and true and joined to your point of view. Because there must be a wing. With the exception of the very occasional balloon, it is only with wings that people rise this high into the stratosphere. And I would not ask you to picture this abstract not-quite-place, this featureless more-than-place, without also having you acknowledge the means by which people come to see such things.

There are stratospheres around other planets. Mars has one; so does Jupiter, and Saturn; Saturn's moon Titan is in the club, too. Spacecraft have measured their heights and their temperatures and sent profiles of them back to Earth – just as orbiters closer to hand have done for the Earth's own stratosphere. But that Earthly stratosphere is not just known from the outside, as the others are, in the planetary way; up here, on the wing, you see it from within, in the way that worlds are seen. There have been no births in this part of the world, though there have been deaths, and few have spent much time here. But what those few achieved here has had human impact. What could be seen from up here helped to determine the early course of the cold war. The damage that might be done to this thinnest of airs did much to define the evolving global environmental consciousness of the of cooler air, leaving no scope for buoyancy to create instability; circulation in the stratosphere, it was to turn out, was side to side, not up and down. Layering was not just possible, it was inevitable. Hence de Bort's name for the new realm he had discovered: the stratosphere is so called because *stratos* means layer. The lower atmosphere, in contrast, he dubbed the troposphere, from *tropos*, to turn or stir.

At the end of the nineteenth century dividing the Earth into concentric spheres with Greek prefixes was becoming popular, a terminological expression of a deeper shift in the way people thought and talked about the planet. The first scientists to take the study of the Earth as their particular domain had been geologists, and they had come to the Earth through rocks, rocks that could be admired in landscapes, collected for museums and mined for money. Their Earth was primarily a history, because it was history, they came to understand, that explained which rocks were to be found where. They sliced up the history of the world ever more finely in space and time, all the time arguing over the sequence and nature of the events for which they thought they saw evidence.

The physicists who turned their imaginations to the planet as a whole (and to other planets too) towards the end of the nineteenth century took a different approach. Only by emphasizing the whole over the parts and the idealized over the specific could the numerical approaches they prized be brought to bear on their new subject. They found dividing the Earth into simplified spheres much more congenial than dividing its history into hard-to-perceive periods. So under the atmosphere (a term which had, as it happened, first been applied to imagined gases around the moon, and only later used to describe the air around the Earth) there was a lithosphere – the stiff rocky shell of the Earth's surface – and a hydrosphere – the oceans. By the early twentieth century all sorts of specialists wanted spheres of their own; glaciologists termed the icy parts of the world the cryosphere, soil scientists took as their subject the pedosphere. Seismologists discovered new spheres within the Earth, atmospheric physicists found new ones in the sky; they eventually stacked three ever-more-tenuous shells – the mesosphere, the thermosphere and the exosphere – on top of the stratosphere.

Those higher realms, though, quickly become otherworldly. They cannot be reached with wings and only barely with balloons; they were not explored before the age of rockets. The stratosphere is the highest realm humans have visited, rather than simply passed through. The first of them to do so, 30 years after its discovery, peered out of tiny windows in metal gondolas hung beneath vast balloons. They rose up in part for adventure, in part for glory, in part for science. There were strange radiations at the top of the world: hard ultraviolet light not seen in the lower atmosphere; the newly discovered 'cosmic rays' held by some to be the birth pangs of new matter. Their more fanciful chroniclers saw the stratonauts pushed up against the boundaries of humankind's narrow reality; Gerald Heard, who wrote science commentaries for the BBC in the 1930s, talked of them being poised to feel the 'untamed energy of the outer universe', of coming close to 'that ocean of energy in which all the suns and raging stars are but mist and spray'.* This sense of being on the edge of immensity is at the heart of the experience of the sublime, a response to the power and scope of nature which, in the words of Edmund Burke, 'fills the mind with grand ideas, and turns the soul in upon itself'. The stratosphere, then and now, offered the sublime in heady drafts.

After the Second World War, flights to the stratosphere became much more common, and wing-borne to boot. They became less about what lay beyond, and more about what sat below; they

* Heard was devoted to the breaking of boundaries, participating in his friend Aldous Huxley's experiments with LSD later in his life, as a polymathic Californian.

also became much more predominantly American. In partially taming some droplets of Heard's ocean of energy, the Manhattan Project changed the way strategists thought about power on a planetary scale. They found in the stratosphere a frontier-free high ground from which the warriors in charge of the new nuclear arsenals could look down; America's first great expression of global power, the B-52 bomber, was accordingly named the Stratofortress. The nuclear age also realigned the interests of the military and those of scientists. Geophysicists, aware that, unlike other physicists, they were largely bereft of laboratories, had come to think of the upper atmosphere as something akin to a replacement, a natural laboratory, and the military, impressed by what physicists had put into the bomb bays of its Stratofortresses, proved happy to offer them better access to it, with rockets and new sorts of aircraft. It also offered them new opportunities to experiment in it.

If there is an emblem for this view of the world, it is the Lockheed U-2, created to serve America's national security, still flying more than 50 years later in the name of science. A remarkable reconnaissance aircraft conceived, built and flown in utter secrecy, it took its pilots far higher than a B-52 could, up to the heights where this chapter began, heights beyond the reach, at least at first, of any interceptors or anti-aircraft missiles. There, the U-2 pilots carried out one of the most important missions of the cold war, attempting to count and pinpoint the USSR's nuclear weapons. From an impervious height, the U-2's elite pilots used cameras finer than any made before to gaze in near omniscience on a world that seemed all but limitless.

And yet, as they did so, the pilots themselves were subject to the tightest of limits. They could see across whole countries; but they could not scratch their own noses, their faces trapped within the helmets of pressure suits no pilots before them had needed. Their wings spanned 40 metres; but they could not stretch their arms or legs, or even reach all the controls in their cockpit without makeshift tools.

Their flight was made possible by the work of thousands of people down below, work carried out at the behest of governments that represented millions more. Yet in the early days of the U-2, the pilots were as alone as it is possible to be, flying thousands of kilometres across enemy territory in radio silence for hour after hour, navigating by the diamond-steady stars (their cockpits had sextants built in). And for all the unimpeded weather-free emptiness of their realm, their flight was constrained within the tightest of aerodynamic envelopes. In air that thin, the difference between flying too fast – and thus being struck down by turbulence – and flying too slow – and thus stalling – was about 20 kilometres an hour. Bank too steeply, and one wingtip would start to tremble as the other stopped providing any lift at all. The pilots had a name for this constraint. They called it the coffin corner.

And yet, for all the boundaries pressing in on them, they could and did appreciate the grandeur of their situation. Even in the coffin corner they could feel at ease among immensities, and joyful in their flight.

Fallout

The U-2 was not just equipped to see. It could sniff as well, detecting some of the aerosols of the upper air *in situ* and also bringing down samples for further study. This was so it could measure a new addition to the stratosphere: nuclear fallout.

Between 1945 and 1963, the United States and the USSR tested hundreds of nuclear weapons, the most disturbing experiments ever carried out by warrior-physicists. Like the radioactive tracers then starting to be used to take pictures of blood vessels, the fallout created and lifted up in these blasts allowed previously invisible processes to be studied. In the mid-1950s Roger Revelle, an oceanographer who was director of the Scripps Institution of Oceanography, used it to look into the absorption of carbon dioxide by the ocean. His studies convinced him, and later his colleagues, that industrial carbon-dioxide emissions could and would change the climate. In tune with the geophysicists' way of thinking about the Earth as a laboratory, he referred to this anthropogenic change as a 'large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future'.*

The U-2s were sent up to sample the bombs' radioactive fallout before it fell, thus providing scientists with insights into both the weapons being tested and the circulation of the stratosphere. Some pilots preferred these missions to the photo-reconnaissance work. For reconnaissance, the aim was to fly as precisely as possible along paths laid down in advance by the intelligence agencies. In sampling missions, on the other hand, the pilots, guided only by the clicking of their Geiger counters, were given the initiative, seeking out the thickest parts of the invisible radioactive slicks, gently climbing and swooping as they looked for the thin layer where the passing fallout was concentrated, flying both with and against the invisible grain of the stratosphere.

Spread around the world by the stratosphere, fallout from nuclear tests eventually settled on soils, in shallow seas, on glaciers and icecaps. With the right instruments, that layer of fallout will be discernible tens of thousands of years from now. It is not necessarily the longest lasting of the marks humankind has left on the face of the Earth, but it is one of the most widely spread and, thanks to the fact that atmospheric testing ended less than twenty years after the first nuclear explosion, one that is very tightly constrained in time. If the Anthropocene ever becomes an

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* A nice coincidence: Revelle's co-author on that paper, Hans Suess, was the grandson of Eduard Suess, the Austrian geoscientist who first introduced the notion of cutting the Earth up into a lithosphere, a hydrosphere and so on in the 1870s.

stratosphere quicker than Libby and the AEC thought; it also did so preferentially in particular parts of North America, Europe, Russia and China – that is, in the belt of land above which the northern jet stream winds its way.

The new idea of the stratosphere as a selective delivery mechanism for fallout, rather than a slow-draining reservoir for it, was ably disseminated by Barry Commoner, a biologist who would go on to become one of the leading environmental activists of the 1960s and 1970s. In an influential book published in 1970, *The Closing Circle*, Commoner formulated four rules of ecology, the first two of which were 'Everything is connected' and 'Everything has to go somewhere', with the explanatory corollary, 'There is no away into which things can be thrown'. The fallout's passage through the stratosphere exemplified both of these rules. The stratosphere was what connected weapon tests in the Pacific with radioactive strontium levels in the bones of children in America. It was not an away into which things could be thrown. It was a component of the earthsystem with its own complex behaviour, linked to what went on below not just by the dynamics of the climate but by the turning winds of politics.

The Ozone Layer

The stratosphere had a supporting role in the first great global environmental issue – that of fallout. It sat out the second such issue – the global spread of organic pesticides such as DDT. But it took a leading role in the third – that of damage to the ozone layer.

Scientists had known since the second half of the nineteenth century that the lack of short-wavelength ultraviolet radiation in sunlight at the surface of the Earth was down to the fact that it was absorbed by ozone in the atmosphere, and some had suspected that that ozone was concentrated at high altitudes. Soon after de Bort discovered the stratosphere, Alfred Wegener, more famous for coming up with the theory of continental drift, suggested that this newly discovered sphere might be the ozone's home, and that turned out to be the case.

The ozone was not just contained by the stratosphere – it was what gave the stratosphere its upside-down character. Absorbing ultraviolet radiation makes the ozone hot. Because the ultraviolet is stronger at height, and because the air higher up is less dense and thus more easily warmed, this absorption heats the top of the stratosphere more than the bottom.

But the ozone does not just sit there maintaining the stratosphere's stabilizing hotter-at-the-top structure. It is constantly being created and destroyed. Ultraviolet radiation breaks down the two-atom molecules of which common-or-garden oxygen consists into individual atoms, which are highly reactive. Some of these atoms react with other two-atom oxygen molecules to make three-atom oxygen molecules – ozone. Some of them react with existing ozone molecules to recreate the more stable two-atom molecules. To make matters more complicated, ultraviolet light breaks down ozone molecules, too – releasing single atoms which go on to take part in further frolics.

These interlinked reactions were first explained by a British physicist, Sydney Chapman, in 1930. He showed how the fact that all of these reactions go on at different rates, some dependent on the temperature, some on the amount of ultraviolet, affects the amount of ozone found at a particular time or season in a given part of the stratosphere; the balance between the processes that create ozone and those that destroy it changes according to the circumstances.

Chapman's spectacularly impressive work established the idea of an 'ozone layer'. It is not, in fact, a well-defined layer. The ozone is distributed through much of the stratosphere, and even at the altitude where it is most concentrated – up in the overworld, at about 25 kilometres – it makes up no more than a four-hundred-thousandth part of the very thin air. If it were a well-defined layer, though, it would be a remarkably thin one – at room temperature and at sea level it would be just 2.5 mm thick – and that fascinated people. Whether talking to each other in academic texts or to the general public in popular articles, scientists speaking of the ozone layer in the 1930s and 1940s never passed up an opportunity to mention this thinness. In an age of concentric geophysical spheres, the very idea that the Earth could have a shell so thin, and that humans could measure it so precisely, was a source of wonder.

It was also seen as evidence of a certain cosmic providence. In 1933 a report from the Associated Press on work by Charles Abbot, astronomer and president of the Smithsonian Institution, made the point in the *New York Times* under an excited stack of headlines: '1/8 inch of ozone alone saves life – Smithsonian Reports on Study of Dr. Abbot of Gas Wall 40 Miles From Earth – sun's death rays barred'. But such a dramatic take on the issue was unusual, and to some unwelcome. *The Times*'s science editor, Waldemar Kaempffert, used his next weekly column to chide his colleagues on the news pages for the inexplicable prominence they had given the report. Many aspects of the atmosphere, Kaempffert pointed out, were necessary for life – the ozone layer was nothing special. When Abbot himself wrote about the subject for the general public, in *The Sun and the Welfare of Man*, the impossibility of life without an ozone layer merited a paragraph or so. In *Exploring the Upper Atmosphere* by Dorothy Fisk, a delightfully eclectic British author of the same vintage, it gets noted in a similarly scant way.

Indeed, Fisk and Abbot both spend considerably more time celebrating the fact that the ozone layer is not thicker – since if it were, humans would be deprived of the longer, softer ultraviolet wavelengths, too. This radiation had recently been shown to be the component of sunlight that caused human skin to generate vitamin D; with less ultraviolet there would be more rickets. In the 1930s, rickets and vitamins were seen as much more interesting than some abstract notion of the habitability of the planet. The ozone layer, Ms Fisk pointed out, was beyond any human influence; vitamins, on the other hand, could be destroyed by over-cooking on the gas cookers spreading into more and more kitchens. That was the sort of threat on which people should concentrate.

At no point in any of this did anyone use the word that today seems almost synonymous with the ozone layer – 'fragile'. The layer was thin, yes – but there was no reason not to think it robust and not to expect it to be permanent. Chapman speculated about the possibility of making holes in it on a temporary basis for the benefit of astronomers, thinking they would learn a lot if they could see the universe as revealed by its ultraviolet emissions; but it was hardly a very serious proposition, and in time the possibility of simply putting the ultraviolet telescopes on to satellites came to seem far more practical. In the 1950s a few scientists interested in the very early history of life gave thought to the fact that, before photosynthesis endowed the atmosphere with significant amounts of oxygen, there would have been no ozone and thus a lot more ultraviolet. But if they saw the vestiges of the ozone layer's beginnings, they saw no prospect of its end.

In the 1960s this began to change. New data showed that Chapman's brilliant chemical analysis could not be the whole story; given the strength of the sun's ultraviolet rays (which could now be measured directly by satellites), more ozone had to be being produced in the stratosphere than Chapman's chemistry predicted. Because Chapman's explanation of the stable level of ozone depended on a balance between the rate of its production and the rate of its destruction, a higher level of production meant there had to be extra processes of destruction, too. None of the gases present in the stratosphere in bulk seemed to be responsible, so the culprit must be a trace gas, one present at lower concentrations even than the ozone itself.

This, more than anything, opened the door to worries that the ozone layer might, indeed, be fragile. Harold Johnston, one of those who spent the 1960s looking for the trace gases responsible for destroying the ozone, later said that he thought, before the fact, that people were 'inclined to assume [that the atmosphere was] impervious to human intervention' simply because there was so much of it. There were, after all, more than a million tonnes of atmosphere per person back then (a bit less than a million now, thanks to population growth). There were hundreds of tonnes of carbon dioxide for each person, and even the ozone layer, so often singled out for its thinness, added up to more than a tonne each. Such amounts seemed to put the earthsystem beyond touch; it simply seemed too big to budge.

The trace gases with which Johnson came to be concerned, though – nitrogen oxides, which scientists abbreviate as NOx – were able to punch above their weight. Each molecule of NOx could shift the stratosphere's chemical balance in such a way as to remove many molecules of ozone. So just a few kilograms per person could make a difference – a small enough amount, Johnson noted, that the inadvertent production of NOx by human industry might drive a global change. There is a general lesson there: humans have found two ways of making a difference to the workings of the earthsystem. One requires large, species-wide effort, such as millennia spent devotedly farming, or a century's concentrated effort devoted to the burning of fossil fuels. The other requires finding a small thing that makes a big difference, as NOx can in the stratosphere – something that offers leverage. The same will apply, as we shall see, when you want to make such differences deliberately. Finding a powerful lever is the key to moving the earthsystem.

By the 1960s there were plans in America, the USSR, Britain and France to develop new airliners that would fly higher in order to fly faster; in doing so they would inject NOx from the Earth by brave pilots, its lower reaches traversed by hundreds of thousands of airline passengers, its integrity challenged by the products of warfare and industry and its protection undertaken by the governments of the world.

The Veilmakers

What more change could another lifetime bring? Come and see. Back up at 22 kilometres, imagine an aircraft similar in shape to the U-2 but bulkier, with stronger shoulders for its long, taut wings. Imagine it not sampling the air, but adding to it – a mist of liquid trailing out behind it all but invisibly, spread through the layers of stable air a few tonnes at a time, eventually forming a layer of aerosols finer than dust. Look to windward and, far off, another aircraft does the same. They are part of a small fleet that flies up here all the time, neither to study nor to spy, but to add to a spreading veil that brightens, very slightly, the haze of the horizon off to one side and lightens, very slightly, the sky as seen from below – a layer that diminishes, just a bit, the amount of sunlight that makes it through the stratosphere to the Earth's surface.

In this big round world these new wings have come to draw a line.

The most widely argued-over form of climate geoengineering is one that would use such a veil to make the world cooler than it would otherwise be. There is much about such an idea to fear. The stories of the wings, and the pilots they carry – the stories that tie the stratosphere into the future world below it – may be stories of ill-informed folly, as those of the SST's swept back wings would have been, or of empire. The pilots of the veilmakers, if the aircraft are designed to need pilots, may be in military uniform, doing with discipline a job that one country and one country alone has decided upon, seeking to tailor the environment to that nation's interests while paying no heed to the interests of any others their actions may harm, either then or further into the future. They may fly with countermeasures to protect them from attack. Their geoengineering may, in itself, constitute an attack on others.

Then again, the pilots might simply be skilled functionaries – professional employees like those who take aircraft from A to B for Federal Express or easyJet in their shirtsleeves. They may be contracted to some international organization that has reasonable standing, and offers convincing reasons, for what it is doing. They may see their task as a distasteful necessity; they may, though, take joy in it, as well as pride. They may be enthusiasts smiling and chatting with tourists who have paid to come along, they may embellish their veilmakers with names from history and fiction – *Beagle* and *Challenger*, *Pequod* and *Surprise*, *Eagle* and *Discovery*, *Tannhauser Gate* and *The Ends of Invention* and *But the Sky, My Lady! The Sky!* Or maybe they wear not flight suits or shirtsleeves but vestments. Maybe they are adepts called to be part of an order that protects the people of the Earth from the extremes of climate.

And whether they are priests or warriors, fanboys or functionaries, they may be misguided.

The rest of this part of the book looks at science's current understanding of how energy flows through the earthsystem, at how veils of fine particles in the stratosphere can provide leverage to alter that flow, and at what effects leaning on such levers could have. There will be details and abstractions, histories and theories, computer modelling and moral philosophy.

Through it all, though, spare the occasional thought for the stratosphere itself, for a play of scattered light on the edge of space, for a boundary, a protection, a vulnerability.

Think of the people up there. Think of the wings that lift them and the stories that build the wings. But, for all that I cherish the idea of looking out at those wings, remember that looking out this way is a privilege. Most people will not look out at the wings; they will look up at them, far, far above, untouchable as angels. Like most of those who look up at wings of all sorts today, they may have little say in where they fly, or at whose command. Some may look with wonder; others may look with unease, with fear, with anger.

Who built those wings? What did they build them for? To what other uses might they be put?

What insignia catches the sun as the aircraft banks on to a new course?

2

A Planet Called Weather

The notion of the global environment, far from marking humanity's reintegration into the world, signals the culmination of a process of separation.

Tim Ingold, 'Globes and Spheres: The Topology of Environmentalism' (1993)

Six years after Tony LeVier, an American test pilot, took off in the first U-2, Yuri Gagarin became the first man to go right through the stratosphere and come out the other side. The missiles the U-2 had been built to peer down on had grown powerful enough to throw people or weapons, according to taste, around the planet or into orbit. Superpower rivalry required that the prowess of these missiles be proved competitively, and so it was. Less than a decade after Gagarin's flight Americans were thrown as far as the moon, and the conflict that threatened to end the world enabled a new appreciation of it.

This chapter is about that new appreciation, and the changes that it brought with it. It is about how the earthsystem works – something which needs to be understood before you think too deeply about how to change it – and how humans think about it. It is thus both about climate science and about the way people think about their environment.

Before the space age, the environment had always been, by definition, the thing one was in. The environment was immediate;