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- Distills the complex data and science into an accessible and visually powerful overview of climate change.
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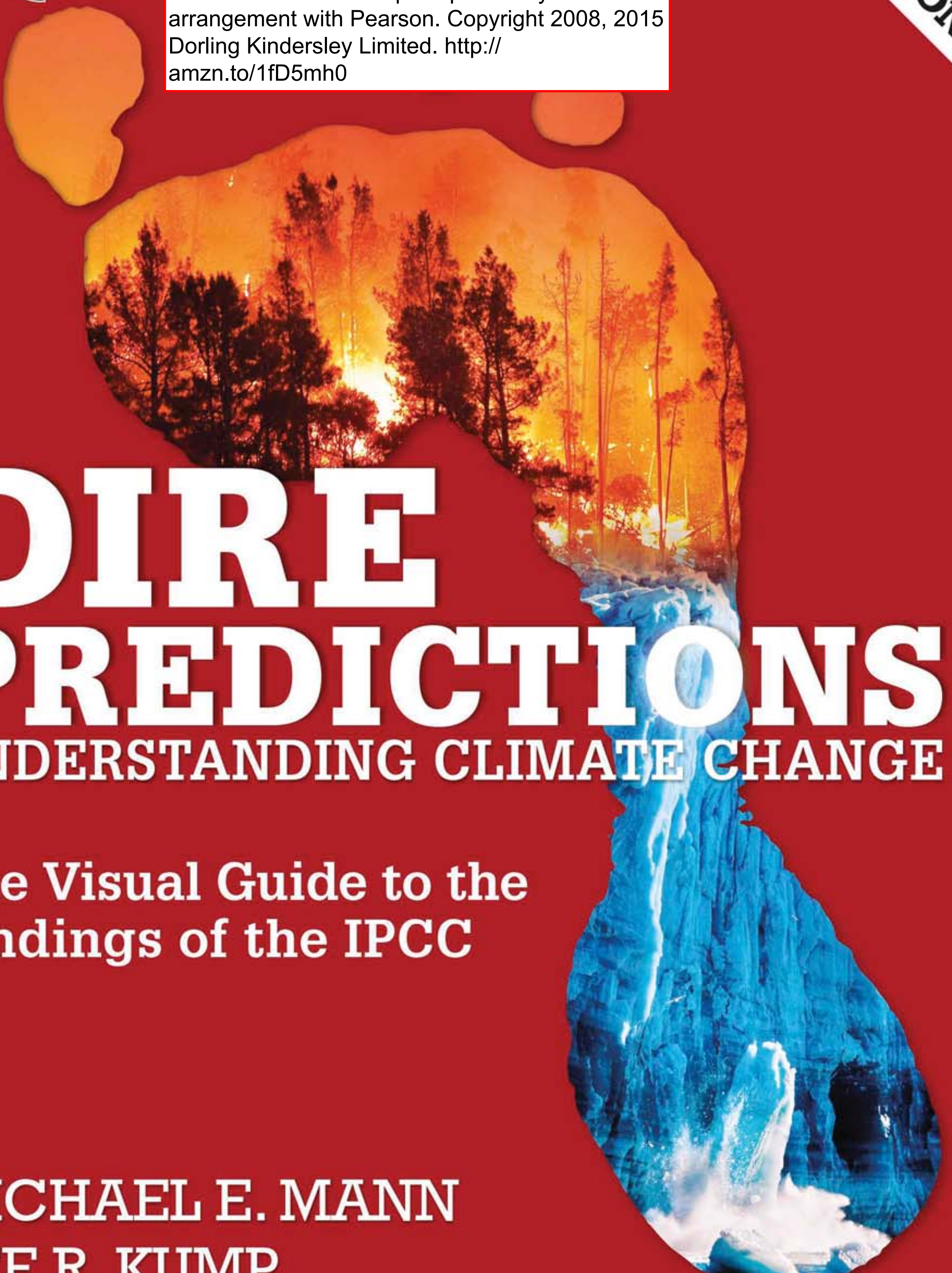

DIRE PREDICTIONS

UNDERSTANDING CLIMATE CHANGE

The Visual Guide to the Findings of the IPCC

MICHAEL E. MANN
LEE R. KUMP

DK Penguin Random House

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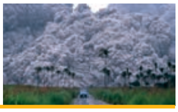

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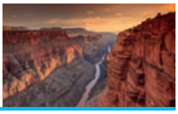

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Taking action in the face of uncertainty

The role of scientists in global policy making

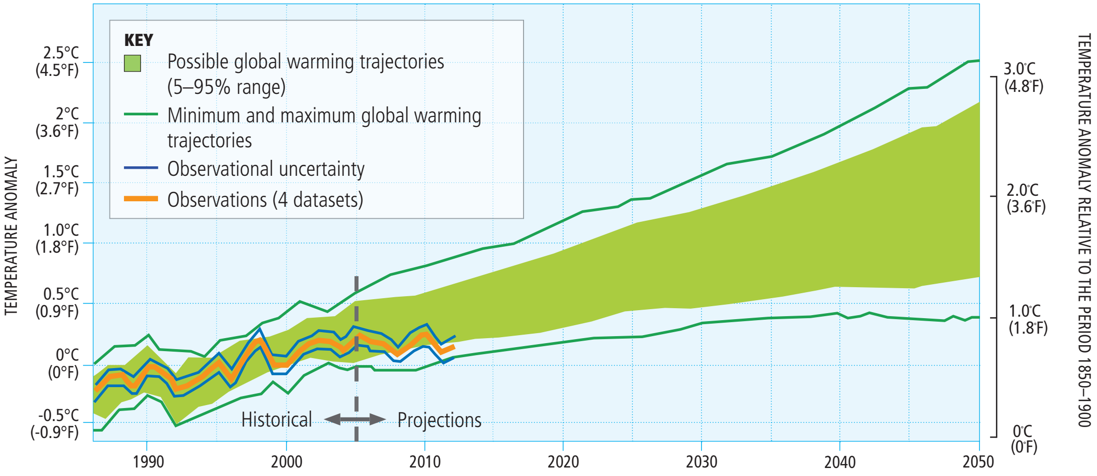
Uncertainty in climate change projections exists whether we like it or not. Some people express skepticism in response to this uncertainty, and cite it as an excuse for inaction. Scientists themselves are trained to be skeptical. They recognize that few things in science can be stated with certainty, that hypotheses can only be disproved, not proved, and that results and conclusions should be expressed in terms of this uncertainty. While scientists can make strong conclusions from uncertain results, others view uncertainty as an indicator of flawed or inadequate scientific approaches.

Why are climate projections uncertain?

In climate science, uncertainty arises from a variety of sources, including the inherently unpredictable nature of aspects of the physical climate system and of the human factors driving climate change; the necessary simplifications that occur when computer models are created; and incomplete knowledge about critical parameters in these models. In determining the likelihood that a conclusion is correct, climate scientists often turn to statistics, but some factors cannot be quantified by data. In these cases, likelihoods can only be established based on expert judgment.

POSSIBLE PATHS OF FUTURE GLOBAL WARMING

Here we see the path warming has taken in the recent past (solid orange line with the uncertainty shown with the blue lines above and below) and a range of possible projected outcomes through the year 2050, based on 300 individual model simulations using various models and various assumptions concerning fossil-fuel use, mitigation strategies, demographic and economic patterns, and assuming no future large volcanic eruptions. The green area includes 90% of the outcomes, whereas the outer green lines encompass all the simulation results. The amount of warming is therefore relative to the average global temperature from 1986–2005 (left scale) or 1850–1900 (right scale).



Scientific conclusions arise from time-tested theories, accurate observations, realistic models based on the fundamentals of physics and chemistry, and consensus among colleagues working in the discipline.

The Fifth Assessment Report

The Fifth Assessment Report of the IPCC presents conclusions in terms of the likelihood of particular outcomes. These are expressed as a probability, based on the quality, volume, and consistency of the evidence and the extent of agreement among experts. Likelihood ranges from virtually certain (more than 99% probability of occurrence) to exceptionally unlikely (less than 1% probability of occurrence).

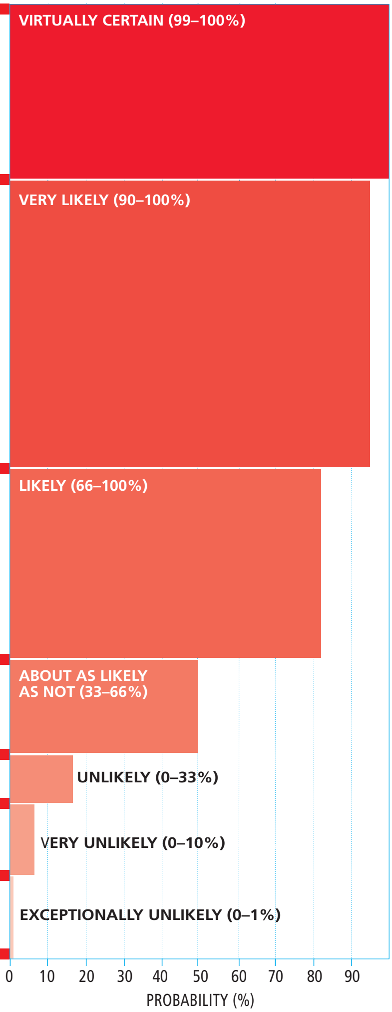
IPCC 5th Assessment Report
http://goo.gl/Vv6sLi

As policymakers are aware, the risk associated with any of these projections is the combination of the *probability of occurrence* and the *severity of the damage* if it were to occur. This means that we should not ignore projections labeled as "unlikely." If any of those events actually occurred, the consequences would be dire.

IPCC PROJECTIONS FOR THE LATE 21ST CENTURY

This table outlines the IPCC's projections for the late 21st century, ranked in decreasing order of certainty.

• Cold days and nights will be warmer and less frequent over most land areas • Hot days and nights will be warmer and more frequent over most land areas • The extent of permafrost will decline • Ocean acidification will incresae as the atmosphere accumulates CO_2 • Northern hemisphere glaciation will not initiate before the year 3000 • Global mean sea level will rise and continue to do so for many centuries	**VIRTUALLY CERTAIN (99–100%)**
• Arctic sea ice cover will continue to shrink and thin, and northern hemisphere spring snow cover will decrease • The dissolved oxygen content of the ocean will decrease by a few percent • The rate of increase in atmospheric CO_2, methane, and nitrous oxide will reach levels unprecedented in the last 10,000 years • The frequency of warm spells and heat waves will increase • The frequency of heavy precipitation events will increase • Precipitation amounts will increase in high latitudes • The ocean's conveyor-belt circulation will weaken • The rate of sea level rise will exceed that of the late 20th century • Extreme high sea-level events will increase, as will ocean wave heights of mid-latitude storms	**VERY LIKELY (90–100%)**
• If the atmospheric CO_2 level stabilizes at double the present level, global temperatures will rise by between 1.5°C (2.7°F) and 4.5°C (8.1°F) • Areas affected by drought will increase • Precipitation amounts will decline in the subtropics • The loss of glaciers will accelerate in the next few decades • Climate change will promote ozone-hole expansion, despite an overall decline in ozone-destroying chemicals	**LIKELY (66–100%)**
• Intense tropical cyclone activity will increase • The West Antarctic ice sheet will pass the melting point if global warming exceeds 5°C (9°F)—this is relative not absolute	**ABOUT AS LIKELY AS NOT (33–66%)**
• Antarctic and Greenland ice sheets will collapse due to surface warming	**UNLIKELY (0–33%)**
• The oceans' conveyor-belt circulation will shut down abruptly • Methane from seafloor clathrates will be released catastrophically	**VERY UNLIKELY (0–10%)**
• If the atmospheric CO_2 level stabilizes at double the present level, global temperatures will rise by <1.0°C (1.8°F) (exceptionally unlikely) or by >6.0°C (10.8°F) (very unlikely)	**EXCEPTIONALLY UNLIKELY (0–1%)**



Greenhouse gases on the rise

How do we know the composition of ancient air?

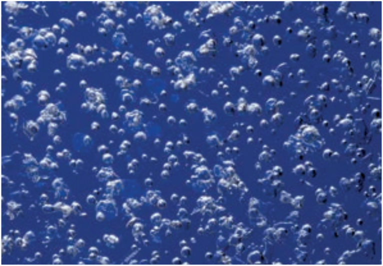
Although scientists have only been measuring the amount of greenhouse gas in the atmosphere for the last few decades, nature has been collecting samples for hundreds of thousands of years.

Over millennia, as snow accumulated on the Antarctic and Greenland ice sheets, the pressure of overlying snow has compressed buried layers of snow into ice. Air trapped in the snow became encapsulated in tiny bubbles. Scientists can drill into those ice sheets, remove samples called ice cores, extract the gas from the bubbles trapped in the ice, and measure the composition of ancient air.

Tragically, the ice-core archive of ancient atmospheres is melting away as climates warm.

Scientists in Antarctica drill into the ice sheet.

An ice core is removed from the drill barrel.



Ancient air
A close-up of a cross-section slice of an ice core clearly shows the tiny bubbles of gas that were trapped when the ice formed.

Distinguishing layers
Ash or dust may show up as dark bands in ice cores. These bands can provide information on wind speeds, desertification, and volcanic eruptions.

The impact of human activity

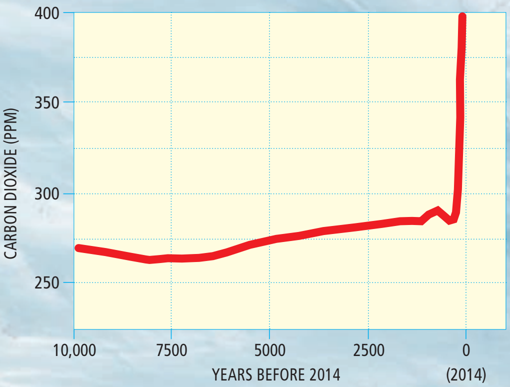
Together with modern observations, analyses of these ice cores reveal the unambiguous human effect on atmospheric composition. As the graphs on the right demonstrate, three greenhouse gases—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—have been rising at dramatic rates for the last two centuries. Driven by fossil-fuel burning, deforestation, and agriculture, the recent skyrocketing trends greatly exceed the natural fluctuations of the preceding hundreds of thousands of years. CO_2 has increased by 40%, CH_4 by 150%, and N_2O by 20%. These gases have a powerful effect on climate, despite the fact that their concentrations are measured in parts per million (ppm) or billion (ppb). You might have to sort through millions of atmospheric molecules to find one of these molecules.

The Greenland ice sheet
An aerial view of the Greenland ice sheet near Baffin Bay, taken in April 2013. The second largest body of ice in the world (after the Antarctic ice sheet), the Greenland ice sheet contains tiny bubbles of ancient air, analysis of which can give information about past atmospheric composition.

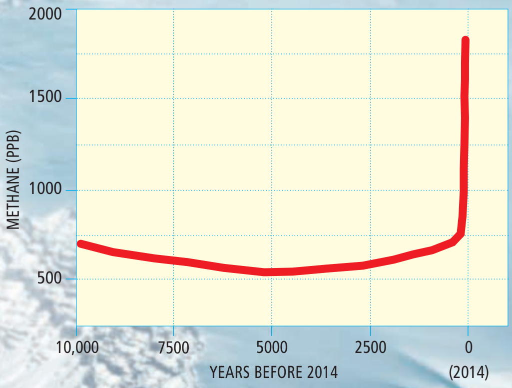
CHANGES IN GREENHOUSE GASES: ICE-CORE AND MODERN DATA

Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide are shown here for the last 10,000 years. Concentrations have increased dramatically since the Industrial Revolution.

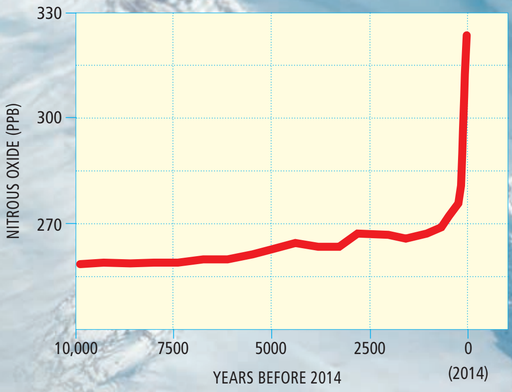
Carbon dioxide



Methane



Nitrous oxide

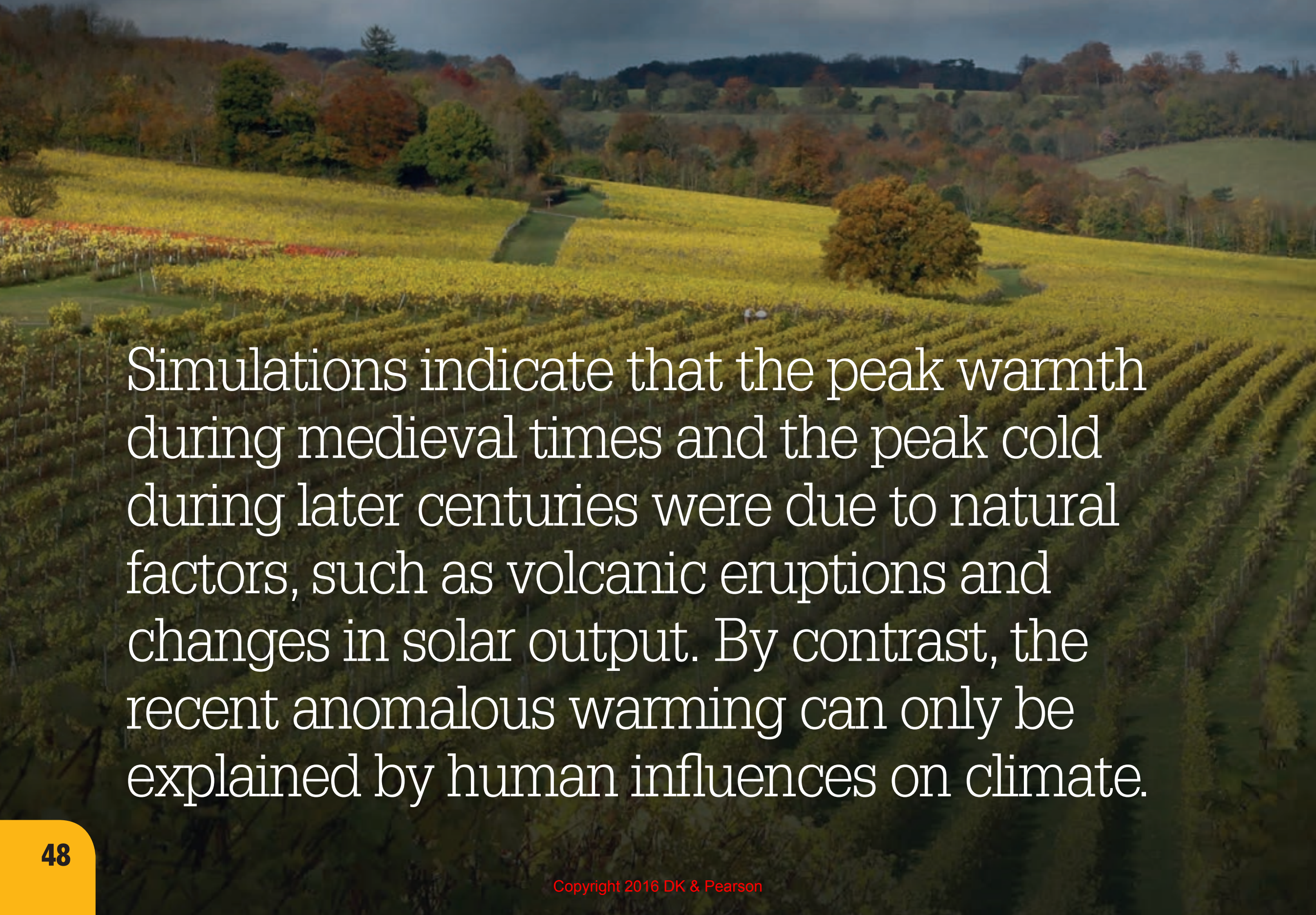


How does modern warming differ from past warming trends?

Some inaccurate accounts of Earth's climate history make reference to a period called the "Medieval Warm Period." It is sometimes asserted, for example, that because Norse explorers were able to establish settlements in southern Greenland in the late 10th century, global temperatures must have been warmer then than now. Supporters of this view also point to the fact that wine grapes were grown in parts of England in medieval times, indicating that local conditions were warmer than they are today. In fact, the ability of the Norse to maintain colonies in Greenland appears to have been related to factors other than regional climate (such as the maintenance of vigorous trade with mainland Europe), and wine grapes are grown over a more extensive region of England today than they were during medieval times.

Actual scientific evidence

So how do modern temperatures compare to those in past centuries, based on the actual scientific evidence? Evidence from **climate proxy** data



Simulations indicate that the peak warmth during medieval times and the peak cold during later centuries were due to natural factors, such as volcanic eruptions and changes in solar output. By contrast, the recent anomalous warming can only be explained by human influences on climate.

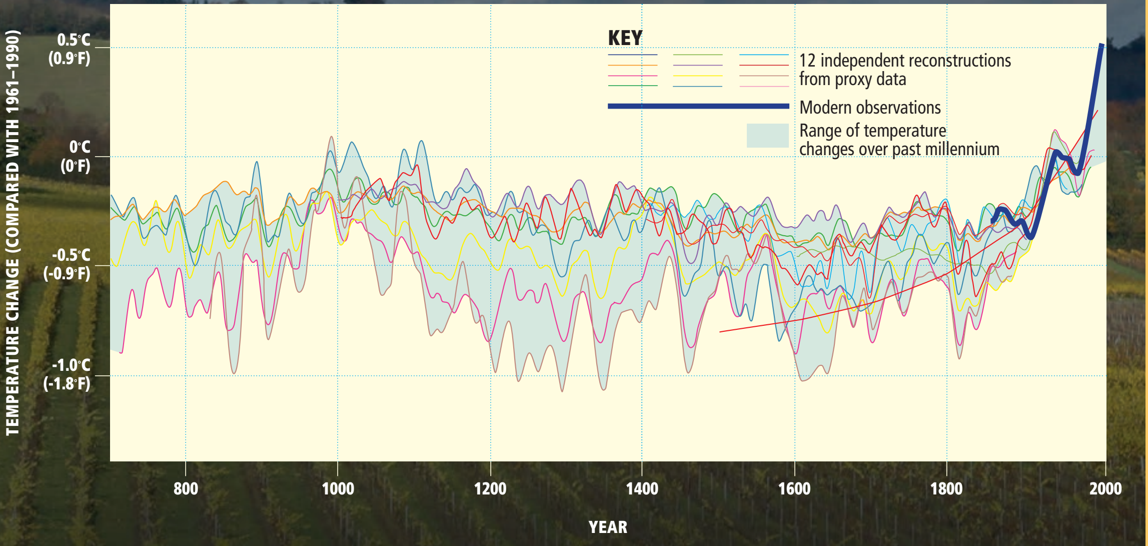
(◂p.42), including tree rings, corals, ice cores, and lake sediments, as well as isolated documentary evidence, indicates that certain regions, such as Europe, experienced a period of relative warmth from the 10th to the 13th centuries, and one of relative cold from the 15th to the 19th centuries (this latter period is often referred to as the "Little Ice Age"). Other regions however, such as the tropical Pacific, appear to have been out of step with these trends.

In fact, the timing of peak warmth and peak cold in past centuries seems to have been highly variable from one region to the next. For this reason, temperature changes in past centuries, when averaged over large regions such as the entire northern hemisphere, appear to have been modest—significantly less than 1.0°C (1.8°F).

Warming everywhere

Unlike the warming of past centuries, modern warming has been globally synchronous, with temperatures increasing across nearly all regions during the most recent century (◂p.35). When averaged over a large region such as the northern hemisphere (for which there are widespread records), peak warmth during medieval times appears to have reached only mid-20th century levels—levels that have been exceeded by about 0.5°C (about 1°F) in the most recent decades.

Vineyards—in England?
Rows of vines in autumn at Denbies Vineyard, Surrey, England, UK



NORTHERN HEMISPHERE TEMPERATURE CHANGES OVER THE PAST MILLENNIUM
A number of independent estimates have been made of temperature changes for the northern hemisphere over the past millennium. While there is some variation within the different estimates, which make use of different data and techniques, they all point to the same conclusion: the most recent warming is without precedent for at least the past millennium.

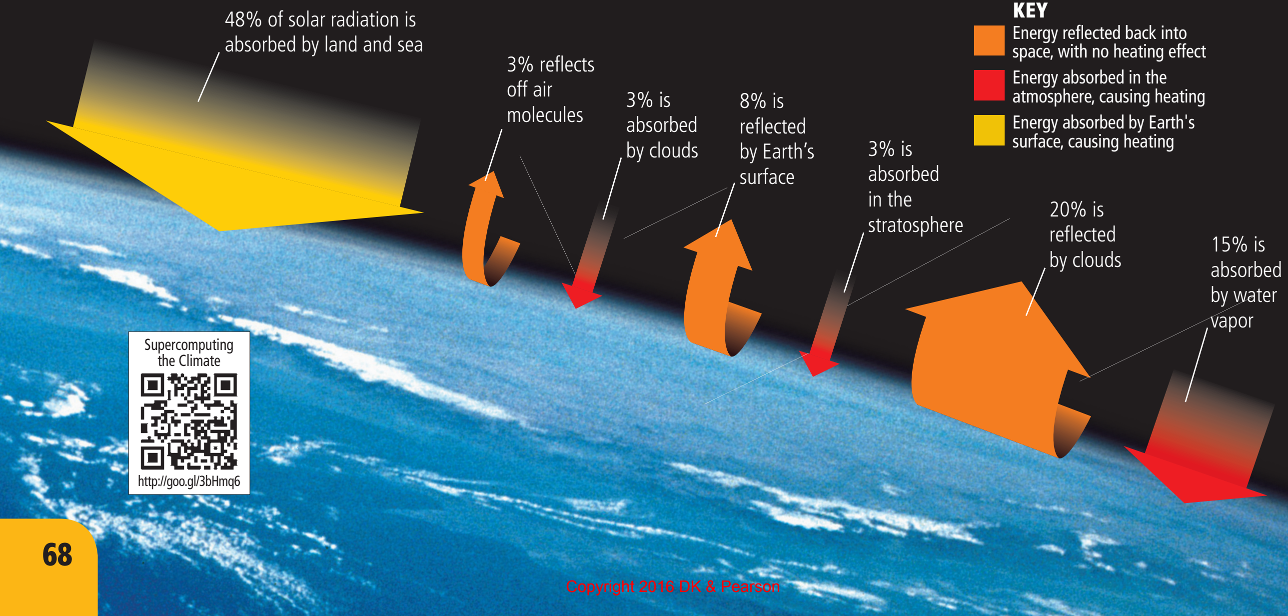
How to build a climate model

Building a model of Earth's climate is a challenging endeavor because the climate is governed by many complex physical, chemical, and biological processes and their interactions. Earth's climate can be thought of as a system with different physical properties (the oceans, atmosphere, and the ice sheets and glaciers in polar and high-elevation regions). Each of these components, and the interactions between them, are governed by the laws of physics: fluid dynamics, thermodynamics, and radiation balance. There are many further complications, however, that must be taken into account in modeling Earth's climate. For example, life on Earth (the **biosphere**), which includes both plants and animals, plays a key role. The biosphere is involved in the global recirculation of water and carbon, and it influences the composition of the atmosphere and Earth's surface properties—all of which impact climate.

Simple climate models

The simplest models ignore the three-dimensional structure of Earth, atmosphere, and oceans, and simply focus on the balance between incoming solar energy and outgoing terrestrial (heat) energy. It is the balance between these incoming and outgoing sources of energy that determines temperatures on Earth. Even in these simple models, the greenhouse effect (◀ p.22) must be accounted for. This is usually accomplished through a modification that represents the way heat is absorbed and emitted by the atmosphere. It is also essential, even in simple models, to account for feedback loops (◀ p.24) that can either amplify (positive feedback) or diminish (negative feedback) the impacts of any changes. In most climate models, the net impact of feedbacks roughly doubles the magnitude of the expected warming or cooling response to imposed changes.

BUDGETING THE INCOMING RADIATION



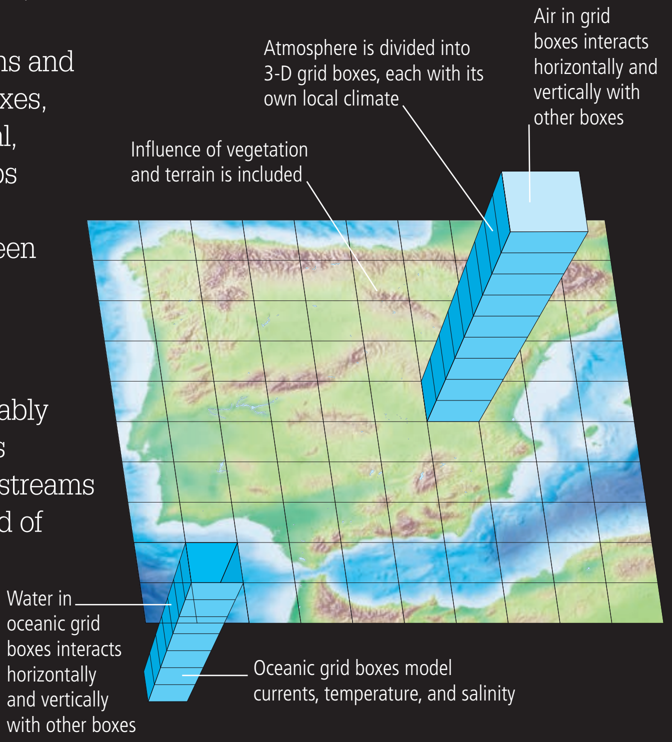
Supercomputing the Climate
http://goo.gl/3bHmq6

Complex climate models

The most complex climate models, referred to as **general circulation models (GCM)**, take into account the full three-dimensional structure of the atmosphere and oceans, arrangement of the continents, details of coastlines and ocean basins, and surface topography. These models calculate not only surface temperatures, but also other important climate variables, such as precipitation, atmospheric pressure, surface and upper level winds, ocean currents, temperatures, and salinity. This is accomplished by breaking the oceans and atmosphere into many small grid boxes, and by using the underlying physical, chemical, and biological relationships to calculate values for properties of each box and the interactions between different boxes.

Should climate model predictions be trusted?

Current climate models do a remarkably good job of reproducing key features of the actual climate such as the jet streams in the atmosphere, the seasonal band of rainfall and cloudiness that migrates north and south of the equator, and even the complex internal climate oscillation associated with the El Niño phenomenon (▶ p.100). These models also closely reproduce past changes (▶ p.72), including the demise of Arctic sea-ice extent, intermittent cooling episodes caused by volcanic eruptions, and past glacial and hothouse climate states. Large-scale rainfall patterns are reasonably well simulated, but finer-scale details are a continuing challenge for the models. Nevertheless, significant progress is being made, and we have good reason to take their projections of possible future changes in climate seriously.



COMPLEX CLIMATE MODELLING

Global climate models divide a region like Spain into a number of grid cells and calculate the energy, moisture, and carbon budgets for each cell. Cells are influenced by the surrounding cells and by incoming solar energy, outgoing Earth energy, and water and carbon fluxes between ocean or land surface and atmosphere. Properties like temperature, humidity, and cloud cover are treated as uniform for the whole grid cell. Thus, higher-resolution models with smaller grid cells tend to perform better but require considerably greater computing power.

LOST ENERGY

Only 48% of incoming solar energy reaches Earth's surface to heat the continents and oceans. Nearly one-third of the total energy that encounters the atmosphere is immediately returned to space—reflected by clouds or air molecules. Additional radiation is reflected by Earth's surface, especially in icy regions. The remainder is absorbed by stratospheric gases and tropospheric clouds and water vapor.

How sensitive is the climate?

Evidence from deep time

As we've seen, studies of climate change over the last few centuries can provide us with reliable estimates of climate sensitivity. These sensitivities correspond to changes in atmospheric CO_2, ranging from the pre-industrial level of 280 ppm to the 2014 value of nearly 400 ppm. While significant, this range doesn't include the known glacial–interglacial variations in atmospheric CO_2 over the last 650,000 years: at the peak of the glacial periods, atmospheric CO_2 dipped to 180 ppm. The range also comes well short of possible future increases in atmospheric CO_2, which are predicted to reach nearly 2000 ppm. So how do we determine how climate will respond to the significantly elevated levels of atmospheric carbon dioxide anticipated for the future? We need to look to the ancient past for clues.

Clues from deep time

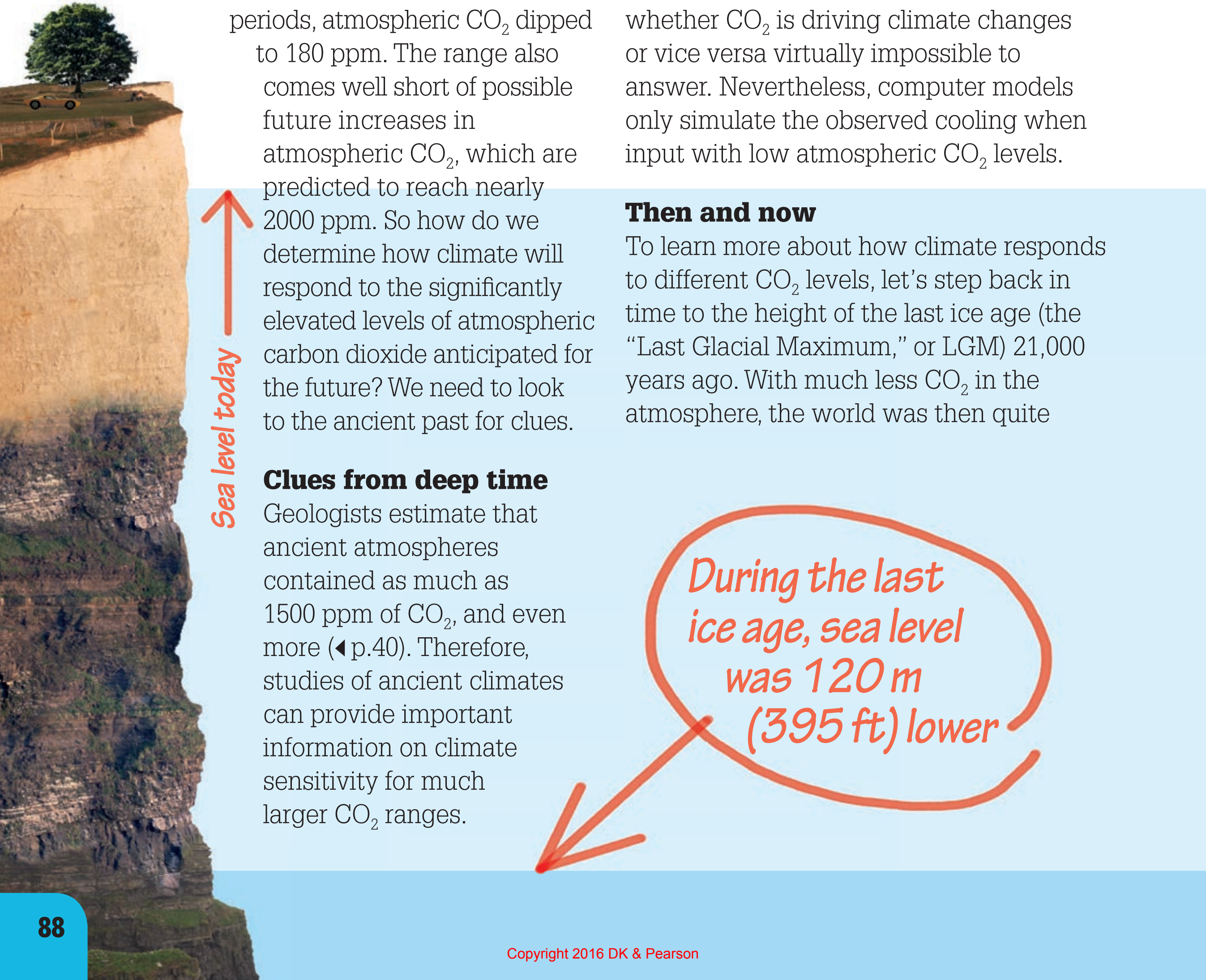
Geologists estimate that ancient atmospheres contained as much as 1500 ppm of CO_2, and even more (◀ p.40). Therefore, studies of ancient climates can provide important information on climate sensitivity for much larger CO_2 ranges.

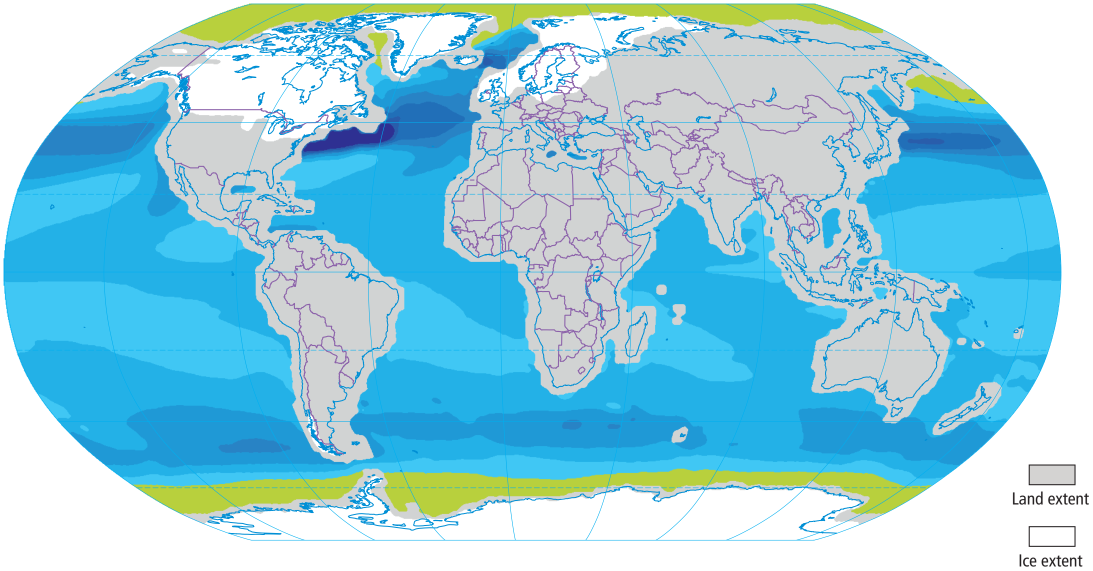
A turbulent past

For the last 2 million years, Earth has been swinging in and out of glacial conditions, driven by subtle changes in Earth's orbit around the Sun that are amplified by feedbacks in the carbon cycle and climate system. Data from ice cores demonstrate that fluctuations in CO_2 and temperature have gone hand in hand for at least the last 650,000 years. Feedback loops in the carbon cycle make the question of whether CO_2 is driving climate changes or vice versa virtually impossible to answer. Nevertheless, computer models only simulate the observed cooling when input with low atmospheric CO_2 levels.

Then and now

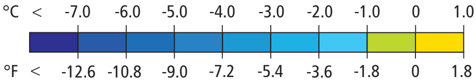
To learn more about how climate responds to different CO_2 levels, let's step back in time to the height of the last ice age (the "Last Glacial Maximum," or LGM) 21,000 years ago. With much less CO_2 in the atmosphere, the world was then quite





HOW MUCH COLDER WAS IT 21,000 YEARS AGO?

Temperature differences between the Last Glacial Maximum, 21,000 years ago, and today, show that the LGM was generally cooler. Mid-to-high latitudes experienced more intense cooling (dark blue), especially near the ice sheets (shown in white) except in the polar seas, where cooling was less intense (green).



SEA SURFACE TEMPERATURE CHANGE (°C/°F) FOR THE LAST GLACIAL MAXIMUM CLIMATE (APPROXIMATELY 21,000 YEARS AGO) RELATIVE TO THE PRE-INDUSTRIAL (1750) CLIMATE.

a different place. The sea level was 120 m (395 ft) lower, because evaporated seawater had fallen as snow and formed the vast ice sheets of the northern hemisphere. A stroll to the beach from Atlantic City, New Jersey, would have taken days, since the shoreline was 80 km (50 miles) east of where it is today. Based on ice-core gas analyses (◀ p.30), we know that the atmosphere's CO_2 content was less than 50% of what it is now. There are other differences between the LGM and today:

- Atmospheric methane was about one-fifth and nitrous oxide was about two-thirds of what they are today.
- Vast ice sheets covered much of Canada, the northernmost U.S., Scandinavia, and northern Europe. These ice sheets were considerably more reflective than the surfaces they replaced. This accounts for half of the cooling, since the ice sheets were reflecting heat rather than absorbing it.
- Earth's orbital configuration was different than it is today (◀ p.66). Because of this, the amount of summer sunshine at high northern latitudes was reduced, so snow from the winter survived the summer and additional ice accumulated.

What can the Last Glacial Maximum teach us about tomorrow's climate?

» (Cont.)

The highway to extinction?

The diversity of species on planet Earth today is the result of millions of years of evolutionary interaction between life and its environment. Human intervention is a new, powerful force, which some liken to the forces that led to mass extinctions of life in the past, such as the asteroid impact that probably precipitated the demise of the dinosaurs 65 million years ago.

Polar bears in danger

A case in point is the precarious future of the polar bear, which depends on expansive sea-ice cover to reach and feed on seals. The earlier spring breakup and retreat of the sea-ice now forces polar bears to remain on the tundra, where they must fast and survive on reserves of fat. This puts particular stress on female polar bears, which spend the winter in nursing dens and need easy access to seals in spring to rebuild their fat reserves.

Temperature changes and limited water availability can stress individual organisms that find themselves suddenly outside of their climate "comfort zone." Typically it is not just one species that is affected. Nearly 60% of widespread and common plant species and 35% of widespread and common animal species will see their habitat ranges shrink by over 50% by 2080.

Bears on ice
Since polar bears hunt on sea-ice, the melting of the Arctic ice cap is making it increasingly difficult for the bears to find sufficient food.

Gone for good?
The golden toad was last seen in the cloud forests of Costa Rica in 1989.

Extinct amphibians

Also of concern is the worldwide loss of amphibians. The golden toad was last seen in the cloud forests of Costa Rica in 1989. In cloud forest ecosystems, mist from clouds is the primary source of moisture. As the climate warms, trade winds rising up the mountain slope condense at higher elevations, so clouds shift upward. Cloudiness increases, but clouds no longer intersect the forest floor, so it gets drier but the nights get warmer. Birds, reptiles, and amphibians have all been affected, but the golden toad and many species of the harlequin frog are now believed to be extinct. Some scientists theorize that warmer nights may favor growth of the chytrid fungus—a potentially fatal pathogen that grows on amphibian skin.

Adapt or die

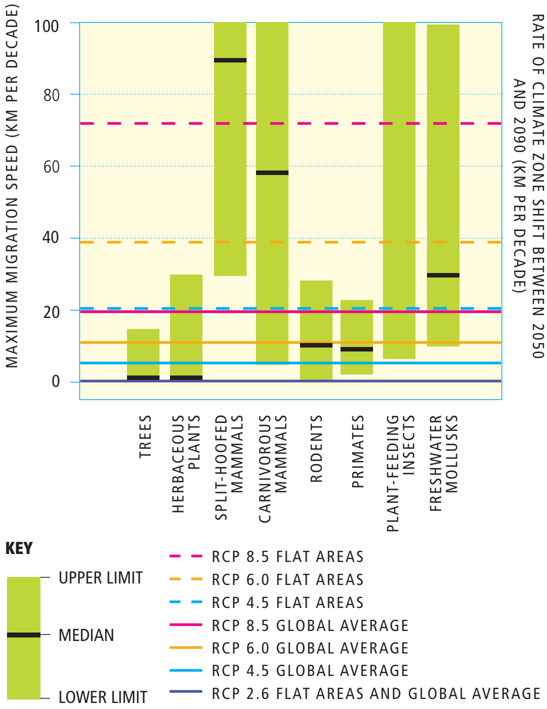
Amphibians are the first group of organisms identified as at risk of extinction from global warming. Many more will follow as the planet warms, especially if the rate of warming is rapid. Organisms adapt and ecosystems migrate at rates that sadly may be too slow to prevent ecosystem collapse and the extinction of species.

The IPCC 4th Assessment Report stated with medium confidence that 20–30% of plants and animals will be subject to increased risk of extinction if global temperatures rise to 2.0°C (3.6°F) above the pre-industrial level, and perhaps 40–70% of species will be at risk of extinction if temperatures rise by 4.0°C (7.2°F). The current report expresses high confidence in these conclusions.

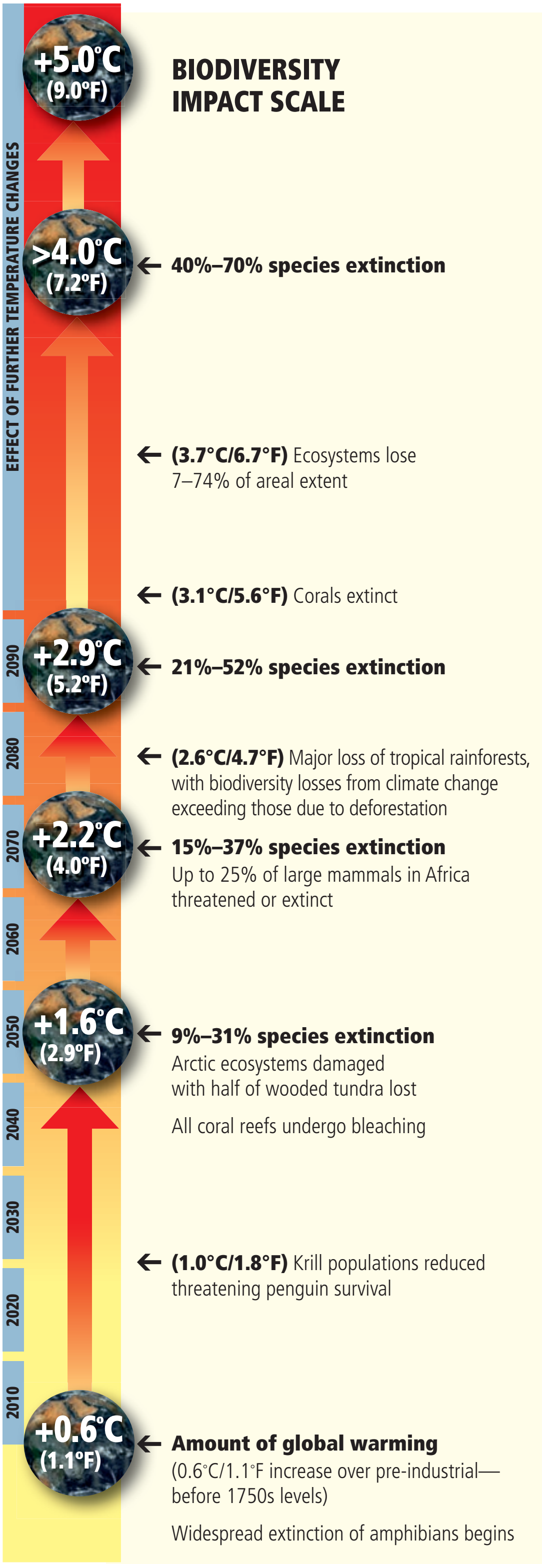
We must remember that extinction is irreversible, and that we are inseparably dependent on the diversity of species harbored by our planet, and the goods and services provided by the ecosystems they support (◀ p.124).

SPEED LIMITS OF MIGRATION

The rates at which climate zones are expected to move under various fossil-fuel emissions scenarios show that climate speeds exceed the natural migration capacities of most plants and animals for the higher-emissions scenarios. Climate zone migration is faster across flat areas (areas with less mountainous relief).



BIODIVERSITY IMPACT SCALE



← **40%–70% species extinction**

← **(3.7°C/6.7°F)** Ecosystems lose 7–74% of areal extent

← **(3.1°C/5.6°F)** Corals extinct

← **21%–52% species extinction**

← **(2.6°C/4.7°F)** Major loss of tropical rainforests, with biodiversity losses from climate change exceeding those due to deforestation

← **15%–37% species extinction**
Up to 25% of large mammals in Africa threatened or extinct

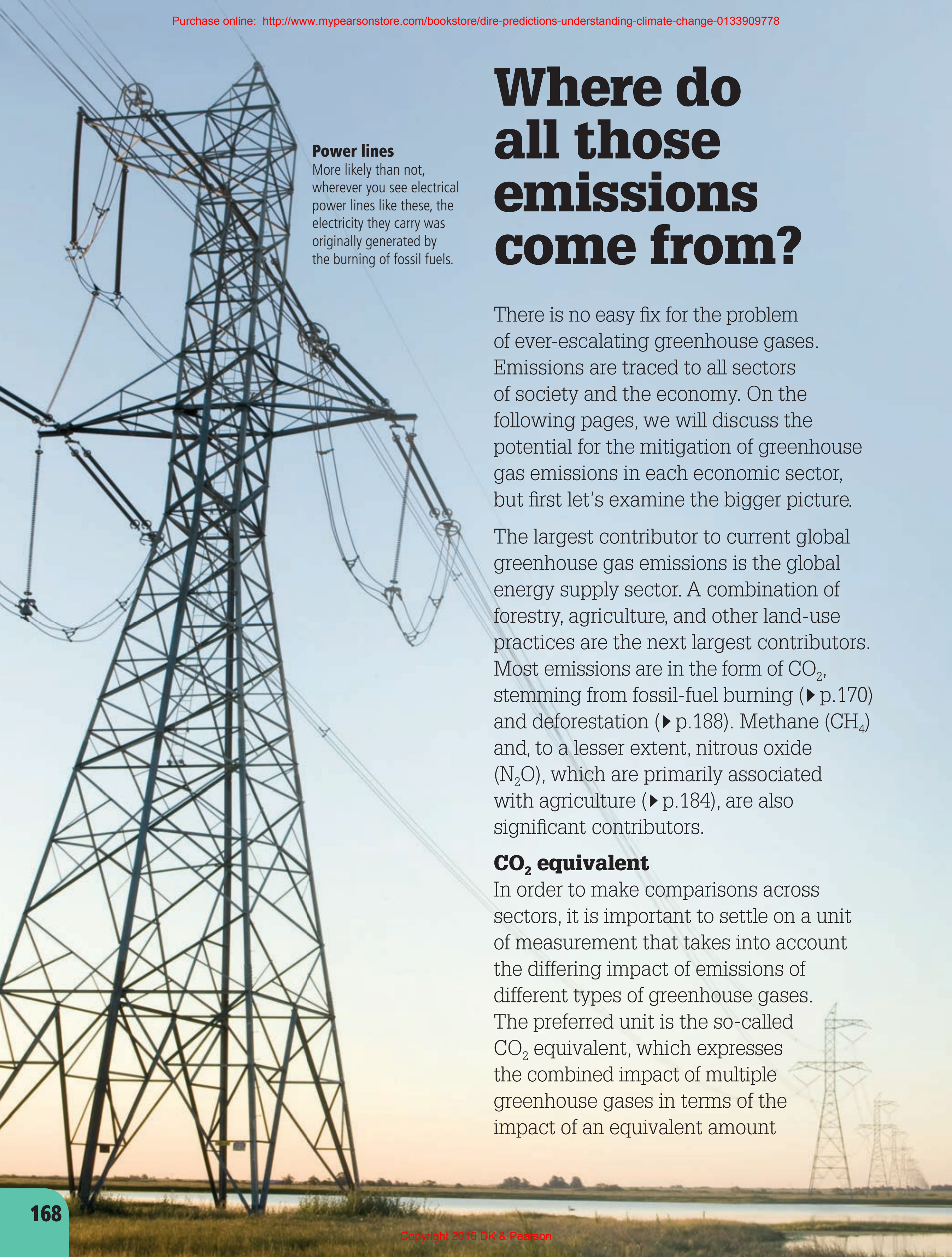
← **9%–31% species extinction**
Arctic ecosystems damaged with half of wooded tundra lost

All coral reefs undergo bleaching

← **(1.0°C/1.8°F)** Krill populations reduced threatening penguin survival

← **Amount of global warming**
(0.6°C/1.1°F increase over pre-industrial—before 1750s levels)

Widespread extinction of amphibians begins



Power lines
More likely than not, wherever you see electrical power lines like these, the electricity they carry was originally generated by the burning of fossil fuels.

Where do all those emissions come from?

There is no easy fix for the problem of ever-escalating greenhouse gases. Emissions are traced to all sectors of society and the economy. On the following pages, we will discuss the potential for the mitigation of greenhouse gas emissions in each economic sector, but first let's examine the bigger picture.

The largest contributor to current global greenhouse gas emissions is the global energy supply sector. A combination of forestry, agriculture, and other land-use practices are the next largest contributors. Most emissions are in the form of CO_2, stemming from fossil-fuel burning (▶ p.170) and deforestation (▶ p.188). Methane (CH_4) and, to a lesser extent, nitrous oxide (N_2O), which are primarily associated with agriculture (▶ p.184), are also significant contributors.

CO_2 equivalent

In order to make comparisons across sectors, it is important to settle on a unit of measurement that takes into account the differing impact of emissions of different types of greenhouse gases. The preferred unit is the so-called CO_2 equivalent, which expresses the combined impact of multiple greenhouse gases in terms of the impact of an equivalent amount of CO_2. The CO_2 equivalent is typically measured in either megatons (millions of metric tons) or **gigatons** (billions of metric tons) of CO_2 (abbreviated as Mt/Gt CO_2 eq).

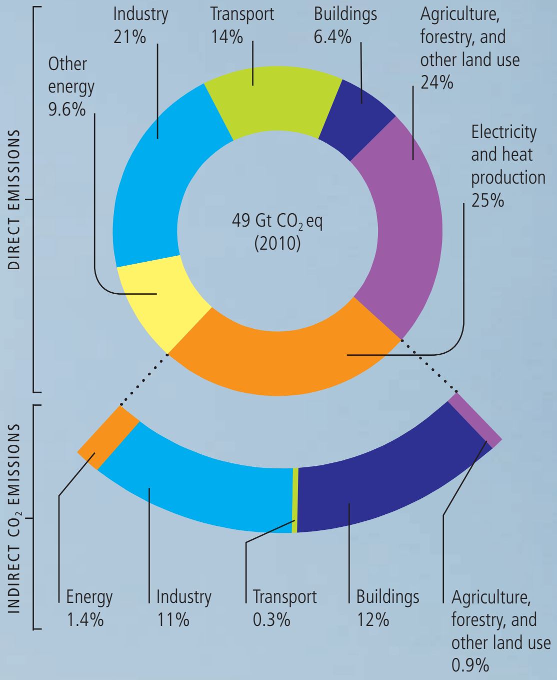
Who emits?

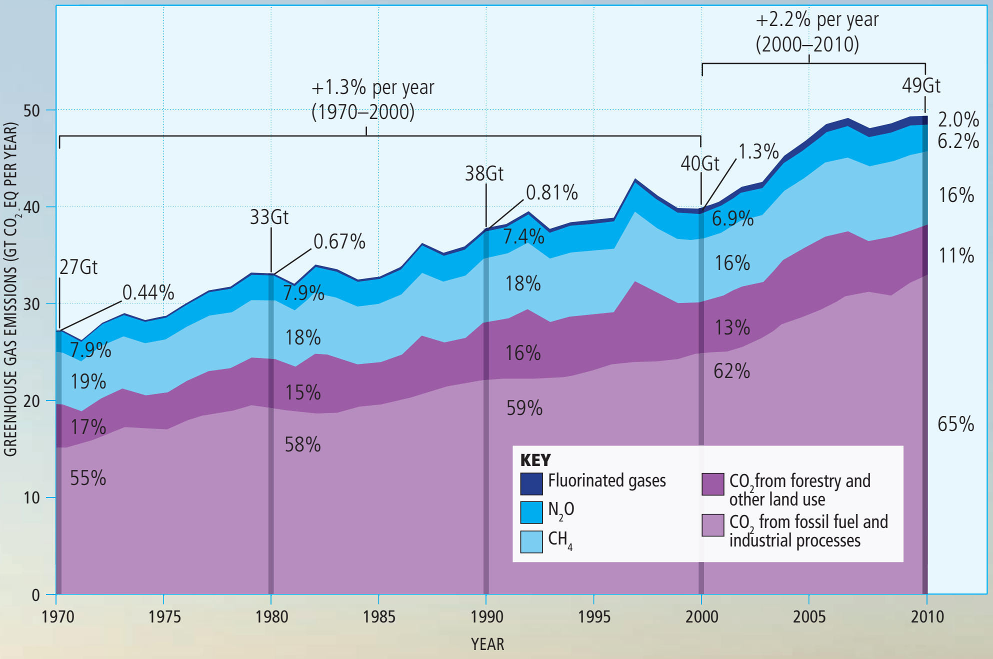
Although the energy supply sector is currently responsible for the largest emissions (nearly 17 Gt CO_2 eq annually), other sectors such as agriculture and forestry (around 12 Gt), industry (around 10 Gt), and transportation (around 7 Gt) continue to contribute substantially to global greenhouse gas emissions.

Over the past four decades, CO_2 emissions from fossil-fuel burning alone have roughly doubled from 16 Gt CO_2 eq to about 32 Gt CO_2 eq annually. Fossil-fuel burning now accounts for approximately two-thirds of total greenhouse gas emissions.

GREENHOUSE GAS EMISSIONS BY SECTOR IN 2010

Electricity generation and agriculture/forestry are responsible for the most greenhouse gases.





TRENDS IN GREENHOUSE GAS EMISSIONS OVER TIME

Carbon dioxide (CO_2) from fossil-fuel burning and deforestation continue to make up the bulk of greenhouse gas emissions.

Geoengineering

Having our cake and eating it too

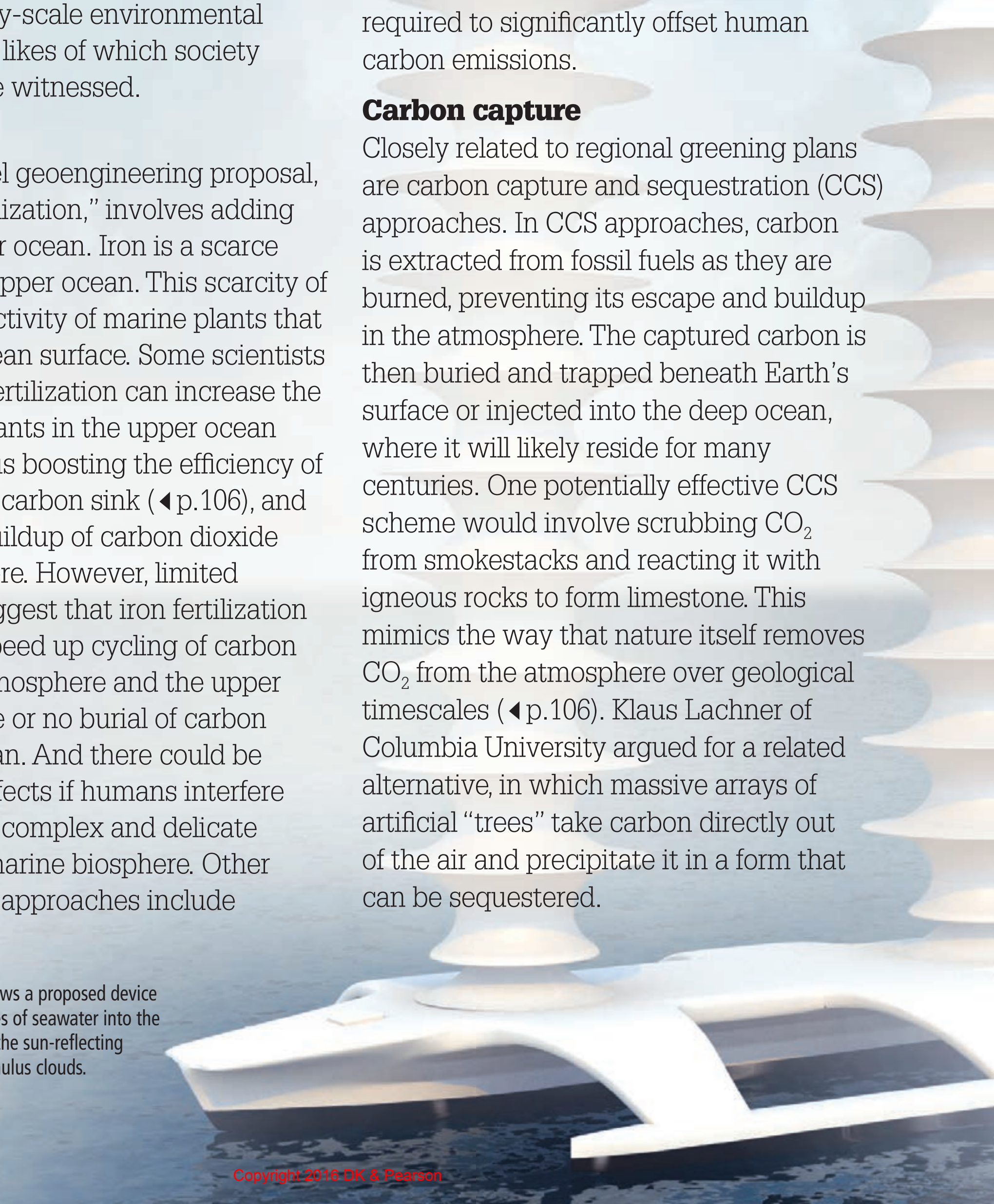
Geoengineering is an alternative approach to mitigation (◀p.154) that involves using technology to counteract climate change impacts either at the source level (doing something about growing greenhouse gas levels) or at the impact level (offsetting climate change itself). Both approaches involve planetary-scale environmental engineering the likes of which society has never before witnessed.

Carbon sinks

One source-level geoengineering proposal, called "iron fertilization," involves adding iron to the upper ocean. Iron is a scarce nutrient in the upper ocean. This scarcity of iron limits the activity of marine plants that live near the ocean surface. Some scientists think that iron fertilization can increase the rate at which plants in the upper ocean take up CO_2, thus boosting the efficiency of the deep-ocean carbon sink (◀p.106), and offsetting the buildup of carbon dioxide in the atmosphere. However, limited experiments suggest that iron fertilization would simply speed up cycling of carbon between the atmosphere and the upper ocean, with little or no burial of carbon in the deep ocean. And there could be negative side effects if humans interfere further with the complex and delicate ecology of the marine biosphere. Other geoengineering approaches include attempts to increase the efficiency of terrestrial carbon sinks by planting more trees and "greening" regions that are currently deserts. Many consider this approach more environmentally friendly than other schemes, but it is unclear if it could be accomplished on the scale required to significantly offset human carbon emissions.

Carbon capture

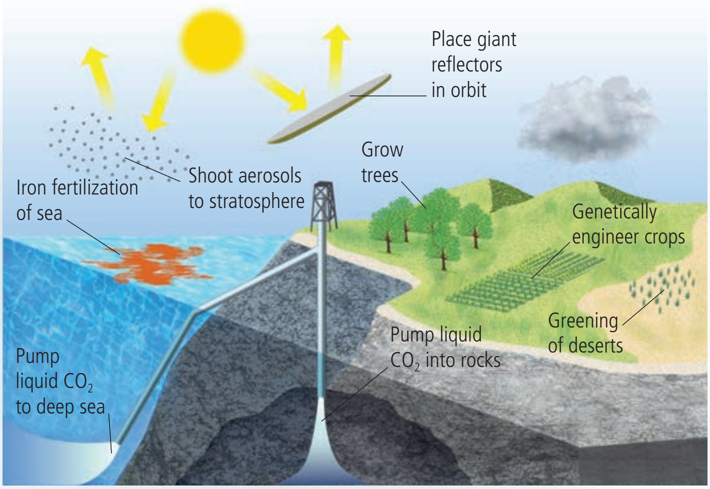
Closely related to regional greening plans are carbon capture and sequestration (CCS) approaches. In CCS approaches, carbon is extracted from fossil fuels as they are burned, preventing its escape and buildup in the atmosphere. The captured carbon is then buried and trapped beneath Earth's surface or injected into the deep ocean, where it will likely reside for many centuries. One potentially effective CCS scheme would involve scrubbing CO_2 from smokestacks and reacting it with igneous rocks to form limestone. This mimics the way that nature itself removes CO_2 from the atmosphere over geological timescales (◀p.106). Klaus Lachner of Columbia University argued for a related alternative, in which massive arrays of artificial "trees" take carbon directly out of the air and precipitate it in a form that can be sequestered.



Saltwater in the sky
This artist's conception shows a proposed device for spraying large quantities of seawater into the atmosphere to help boost the sun-reflecting power of marine stratocumulus clouds.

Solar shields and aerosols

A frequently proposed impact-level geoengineering approach involves deliberately decreasing the amount of sunlight reaching Earth's surface so that the reduction in incoming radiation offsets any greenhouse warming. One method involves deploying vast "solar shields" in space that reflect sunlight away from Earth. Shooting sulphate aerosols into the stratosphere to mimic the cooling impact of volcanic eruptions (◀ p.18) is a less costly but potentially more dangerous alternative. This method could exacerbate the problem of ozone depletion by tampering with the chemical composition of the stratosphere.



GEOENGINEERING SOLUTIONS TO CLIMATE CHANGE

The geoengineering schemes illustrated here could manipulate the composition of our atmosphere and oceans to offset the impacts of burning fossil fuels.

While calculations suggest that either of these impact-level methods could offset greenhouse warming of the atmosphere, each has problems. First, they do nothing to avert the problem of ocean acidification associated with increasing atmospheric CO_2 levels (◀ p.126). Furthermore, climate models indicate that reducing the incoming solar radiation, while potentially offseting the warming of the globe, would not necessarily counteract the regional impacts of greenhouse warming. Some regions might warm at even greater rates, and patterns of rainfall and drought could be dramatically altered. And if, for some reason, these methods were ultimately halted, the full impact of warming that had been masked for decades would suddenly be unmasked, leading to dramatic, rapid global climate change.

Schemes of last resort

Each of the proposed geoengineering schemes has possible shortcomings and poses a potential danger. Some advocates maintain that if we are backed into a corner and faced with the prospect of irreversible and dangerous climate change, we may need to resort to these schemes at least as partial solutions. Industrialists like former Microsoft CEO Bill Gates and Sir Richard Branson of the U.K. have thrown their weight and money behind geoengineering research. Some scientists advocating geoengineering have gone so far as to form start-ups that would profit from the implementation of these schemes. Others note that it would be wise not to tamper with the climate, the workings of which we still do not entirely understand. Either way, the debate over whether geoengineering is likely to be an effective and prudent solution to climate change is bound to continue—as scientists continue to propose new technology to address climate change problems.

But what can I do about it?

If all this talk about energy sectors and governmental buy-in leaves you feeling helpless in the face of global warming, don't let it! Our lifestyle choices can directly aid in the mitigation of greenhouse gas emissions. Often, these are "no regrets" changes that have positive side benefits—improving our quality of life, conserving natural resources, and facilitating greater environmental sustainability.

Lifestyle choices

First, we can be more efficient in our use of energy. We can make home improvements that decrease the energy we use to heat and cool our houses and apartments. More efficient practices include better insulation, passive solar heating, and using fans or opening windows for air conditioning. We can replace inefficient incandescent light bulbs with more efficient bulbs. An important recent trend involves "smart houses," where thermostats can be programmed and remotely controlled for maximum efficiency, where occupancy sensors can be used to minimize the unnecessary use of lighting, and smart power strips eliminate "phantom energy" by automatically sensing power use and reducing power drainage by appliances in standby mode. There is also significant mitigation opportunity in simply being better about recycling.

There are other changes we can make that don't require that we remodel or even buy new appliances. Clotheslines make an excellent substitute for dryers, and unplugging appliances that are not in use helps reduce electricity leakage.

We can make serious contributions to emission reduction efforts with our transportation choices. Many of us could commute to work by bicycle or on foot. For those of us who have difficulty finding

Decrease the amount of energy used in your home by installing solar panels.

Maximize energy efficiency in your home by using a "smart" energy management system.

Drive alone less or drive an electric or hybrid vehicle.

Clotheslines make an excellent substitute for electric dryers.

time to maintain fitness regimes, this option allows for the best sort of multitasking—we exercise while reducing our carbon footprints.

Other alternatives include public transportation and carpools. Hybrid and electric vehicles are another exciting new option. Given the high cost of gasoline in recent years, this option not only benefits the environment, but our pocketbooks as well.

Education and incentives

Employers, governments, and non-governmental organizations can play an important role. Community-focused organizations can provide relevant guidance and education to individuals. Some governments already provide tax benefits and incentives for citizens who build green, add solar panels to their roof, or buy hybrid vehicles. Public outreach efforts can also include educational programs that teach energy conservation practices, and campaigns aimed at encouraging individuals to make environmentally conscious decisions. If you want to know how well you are doing in terms of your own contribution to global greenhouse gas emissions, turn to p.198.

Commute to work by bicycle or on foot.

Replace incandescent bulbs with energy-efficient bulbs.

Appliances that are not in use can be unplugged, reducing electricity leakage.

Remember to recycle.

The known unknowns & unknown unknowns

There are at least two kinds of unknowns. There are the "known unknowns," which are the questions we already know to ask, but for which we don't yet have the answers. Then there are the "unknown unknowns." These are the questions we don't even know to ask, the questions involving phenomena that currently lie beyond the horizons of our imagination.

A great deal of discussion in this book is devoted to the known unknowns. We have discussed the open scientific questions regarding how much warming is to be expected and precisely what the pattern of climate change will be. These uncertainties are linked to unknowns regarding the societal and environmental impacts of climate change (e.g., changes in water availability, food supply, and disease prevalence). We have examined the still-unsolved mysteries of the great climate changes in Earth's past, and the changes in violent weather phenomena, such as hurricanes, that may lie in store for us in the future.

More known unknowns

The known unknowns also include the lack of certainty regarding the "tipping points" looming in our future. Scientists recognize that such tipping points probably exist, but they don't know exactly where they may lie:

- Just how rapidly will the major ice sheets melt, and how high will the sea level rise accordingly? (Recent studies indicate that the loss of ice from the Antarctic and

"Drunken" trees
These treees in Fairbanks, Alaska, have fallen due to melting of the permafrost beneath them, itself a result of rising Arctic temperatures. Permafrost melting also results in the release of the greenhouse gases methane and carbon dioxide, although the full effects of this release on the climate are not yet known.

Greenland ice sheets (◂pp.110–111), and associated contributors to sea level rise, may be proceeding faster than concluded even in the latest IPCC report.)

- Will the “conveyor belt” ocean circulation weaken? And if so, when?
- Will the ability of the oceans and plants to absorb the CO_2 we are adding to the atmosphere change in the future?

Also included in the known unknown category are answers to questions relating to the unpredictability of human behavior.

- What will future human-driven emissions patterns be?
- What will the economic implications of warming be?
- What steps will we take to mitigate against greenhouse gas buildup and climate change? How successful will mitigation efforts be?
- Will we implement any of the currently conceived geoengineering plans? Will new, risk-free plans be conceived of?

Unknown unknowns

And what about the unknown unknowns? There are some of these in the science itself:

- Will the response of the climate to increased greenhouse gas concentrations take an unpredicted course?
- What are the tipping points that have not been conceived of yet?
- Are there hidden reserves of carbon on our planet that could suddenly be released, leading to further warming? (Recent observations of methane escaping from Arctic permafrost and continental shelves suggest the possibility that certain feared carbon cycle feedbacks may already be kicking in.)

In the case of adaptation and mitigation, the unknown unknowns may be the stuff of science fiction. Decades ago, who would have imagined modern-day technology such as cloning or hand-held “smart phones” as powerful as the supercomputers of previous decades? More to the point, who would have conceived of modern transportation options such as hybrid vehicles, or prospective energy technology such as creating genetically altered bacteria that generate propane rather than produce cell membranes?

So what are we to make of all of this uncertainty?

Clearly, we must work to diminish the uncertainty where possible, particularly when it impacts our ability to make appropriate policy decisions or choose an optimal strategy for mitigating climate change. Recent history has taught us that uncertainties are not adequate justification for avoiding action. We know enough today to understand how vital it is that we act now.

Into the unknown
Like this scuba diver exploring an underwater cave in Mexico’s Yucatan Peninsula, we might discover previously unsuspected phenomena as we continue to investigate climate change.