WATER

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April 22, 2021

INTRODUCTION[1]

In its home-page on World Water Day the United Nations points out the following facts:

- **Today, 1 in 3 people live without safe drinking water.**
- **By 2050, up to 5.7 billion people could be living in areas where water is scarce for at least one month a year.**
- **Climate-resilient water supply and sanitation could save the lives of more than 360,000 infants every year.**
- **If we limit global warming to 1.5^{o}C above pre-industrial levels, we could cut climate-induced water stress by up to 50%.**
- **Extreme weather has caused more than 90% of major disasters over the last decade.**
- **By 2040, global energy demand is projected to increase by over 25% and water demand is expected to increase by more than 50%.**

Clearly, water is a crucial resource, and the future well-being of human society depends on how we we manage our global supply of fresh water.

This book discusses various aspects of the relationship of water with human society, and with all life on planet earth. Because of climate change, some regions are increasingly threatened by drought, while others experience catastrophic floods.

Water tables throughout the world are falling, as aquifers are overdrawn. Falling water tables in China were the reason why that country adopted its one-child policy. Because of water shortages, China may soon be unable to feed its own population, but, as Lester R. Brown has pointed out, this will not cause a famine in China, but as China increasingly buys grain on the world market, the price will increase beyond the purchasing power of some of the poorer countries, and it is here that the Chinese water shortages will cause famine.

[1] This book makes use of some of my previously published book chapters and articles, but a large part of the material is new.

I fear that by the middle of the present century, growing populations, water shortages, the effect of climate change on agriculture and the end of the fossil fuel era will combine to produce a famine involving billions of people, rather than millions. Today the high-yield Green Revolution crop varieties have warded off famine, but these varieties are dependent on intensive irrigation and heavy use of fertilizers (often produced today with the aid of fossil fuels). Thus, high-yield agriculture may be difficult to maintain in the future.

The last two chapters of this book are devoted to the role of water in biological specificity, upon which life depends, and the role of water in the origin of life, both on earth, and elsewhere in the universe.

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SHORTAGES OF FRESH WATER

1.1 Climate change and rainfall

The top water-stressed countries in 2140

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7. Palestine
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19. Morocco
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23. Pakistan
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26. Turkmenistan

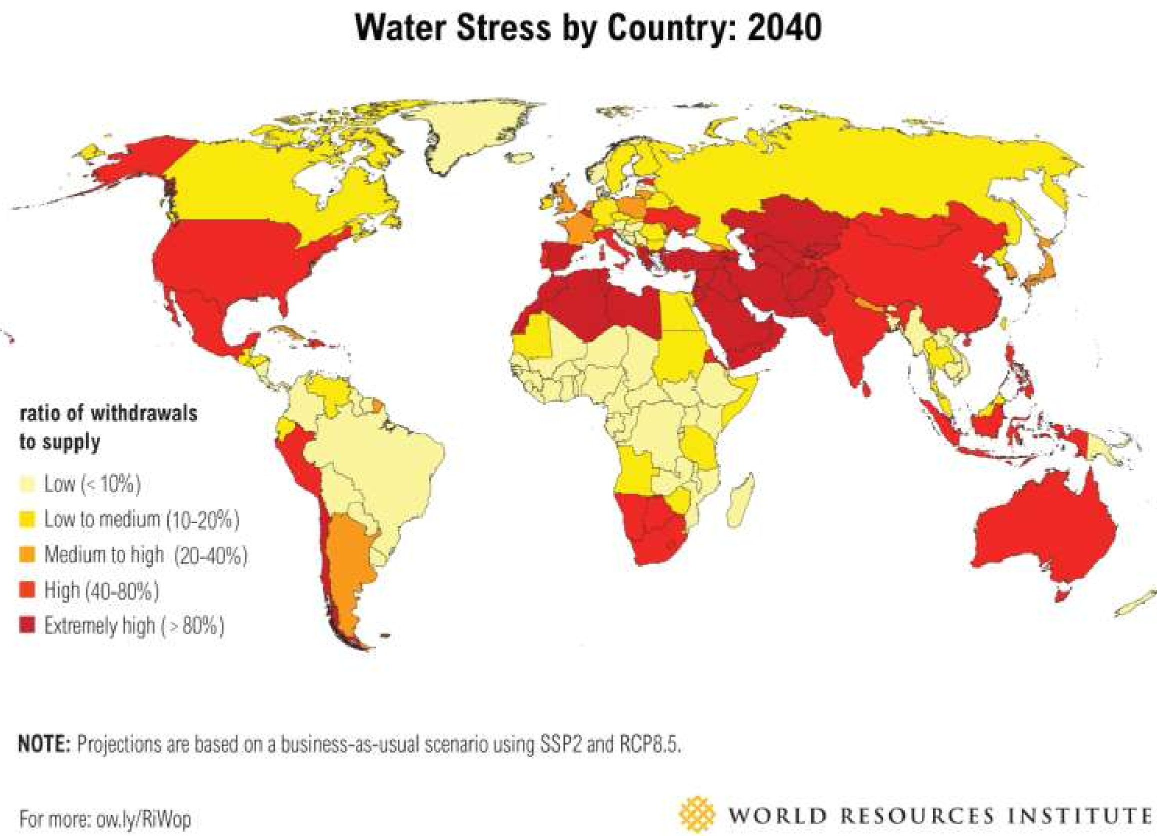

Figure 1.1: **Because of climate change, many of the world's countries will experience water stress by 2140.**

27. Turkey
28. Greece
29. Uzbekistan
30. Algeria
31. Afghanistan
32. Spain
33. Tunisia

1.2 Drought in the Middle East

The Wikipedia article entitled "Climate change in the Middle East and North Africa" makes the following statement:

"The Middle East and North Africa currently faces extreme water scarcity, with twelve out of the 17 most water stressed countries in the world deriving from the region.[32] The World Bank defines an area as being water stressed when per person water supplies fall below 1,700 cubic meters per year. The water supply across the MENA region is averaged at 1274 cubic meters per capita, with some countries having access to only 50 cubic meters per person. The agricultural sector within the MENA region is heavily dependent on irrigation systems due to its arid climate, with 85% of fresh water resources being utilized for agricultural purposes. The IPCC indicate that the global distribution of rainfall is currently shifting in response to increasing greenhouse gas emissions, with increases in high latitude and mid-latitude wet region and decreases in equatorial dry regions such as the MENA. These shifting precipitation patterns have already placed significant strain on MENA agriculture, with the frequency and severity of droughts rising significantly in the past decade.

"A recent NASA study suggests that the 1998-2012 drought in the Middle East was the worst to occur in the past 900 years. Climate scientist Colin Kelley suggests that climate change was a significant contributor to the increased severity of the most recent drought in the region. He claims that such drought is 3 times more likely to occur due to human influence on climate and the drought have contributed to the beginning of the Syrian civil war. Along with environmental impacts, increasing drought periods affect agricultural incomes, diminishes public health and weakens political stability in the MENA region..."

Figure 1.2: **Middle East water crisis brings misery.**

1.3 Drought in Africa

Both the Horn of Africa and Southern Africa have been increasingly plagued by droughts in recent years. Millions of people are now threatened with starvation because of failing agriculture and deaths from lack of water among cattle herds. In Zimbabwe, grain production is down by 53%.

Michael Charles, head of the International Federation of the Red Cross and Red Crescent's Southern Africa Group said: "This year's drought is unprecedented, causing food shortages on a scale we have never seen here before. We are seeing people going two to three days without food, entire herds of livestock wiped out by drought, and small-scale farmers with no means to earn money to tide them over a lean season."

Water levels on the Zambezi River are lower than they have been for decades, and Victoria Falls has become a trickle. Fish stocks on the river are in danger of collapsing.

According to the World Food Program, southern Africa has only received normal rainfall once during the past five years.

Figure 1.3: **Carcasses of sheep and goats amidst a severe drought in Waridaad in the Somaliland region**

Figure 1.4: **Cape Town's largest reservoir, Theewaterskloof, was at 11% capacity in March 2018.**

1.4 Drought in Asia

India

Historically, droughts have lead to terrible famines in India, for example those in the following list:

- The Bengal famine of 1770, in which up to one third of the population in affected areas died.
- The 1876-1877 famine, in which over five million people died.
- The 1899 famine, in which over 4.5 million died.

China

The plateau province of Yunnan in southwest China has encountered its worst drought in many years. As of April 15, 2020, 1.48 million people and 417,300 large domestic animals faced drinking water shortage, and 306,667 hectares of crops were damaged, according to the provincial water conservancy department. Some 100 rivers in the province were cut off, 180 reservoirs dried up, and 140 irrigation wells had an insufficient water supply, figures of the department showed.

Figure 1.5: **The plateau province of Yunnan in southwest China has encountered its worst drought in many years.**

Figure 1.6: **First time heavy Drought condition of Vena Lake during Summer outskirts of Nagpur City in Maharashtra, India. In 2019, India witnessed the second driest pre-monsoon season in the last 65 years. Last year, Chennai ran out of the water in the monsoon months of 2019, where temperature soared to 40 degrees Celsius. It is the sixth-largest city of India and home to about five million people. According to Niti Ayog, a government organization, 21 Indian cities - including Delhi, Bengaluru, Chennai, and Hyderabad - are expected to run out of groundwater, and 40% of India's population will have no access to drinking water by 2030.**

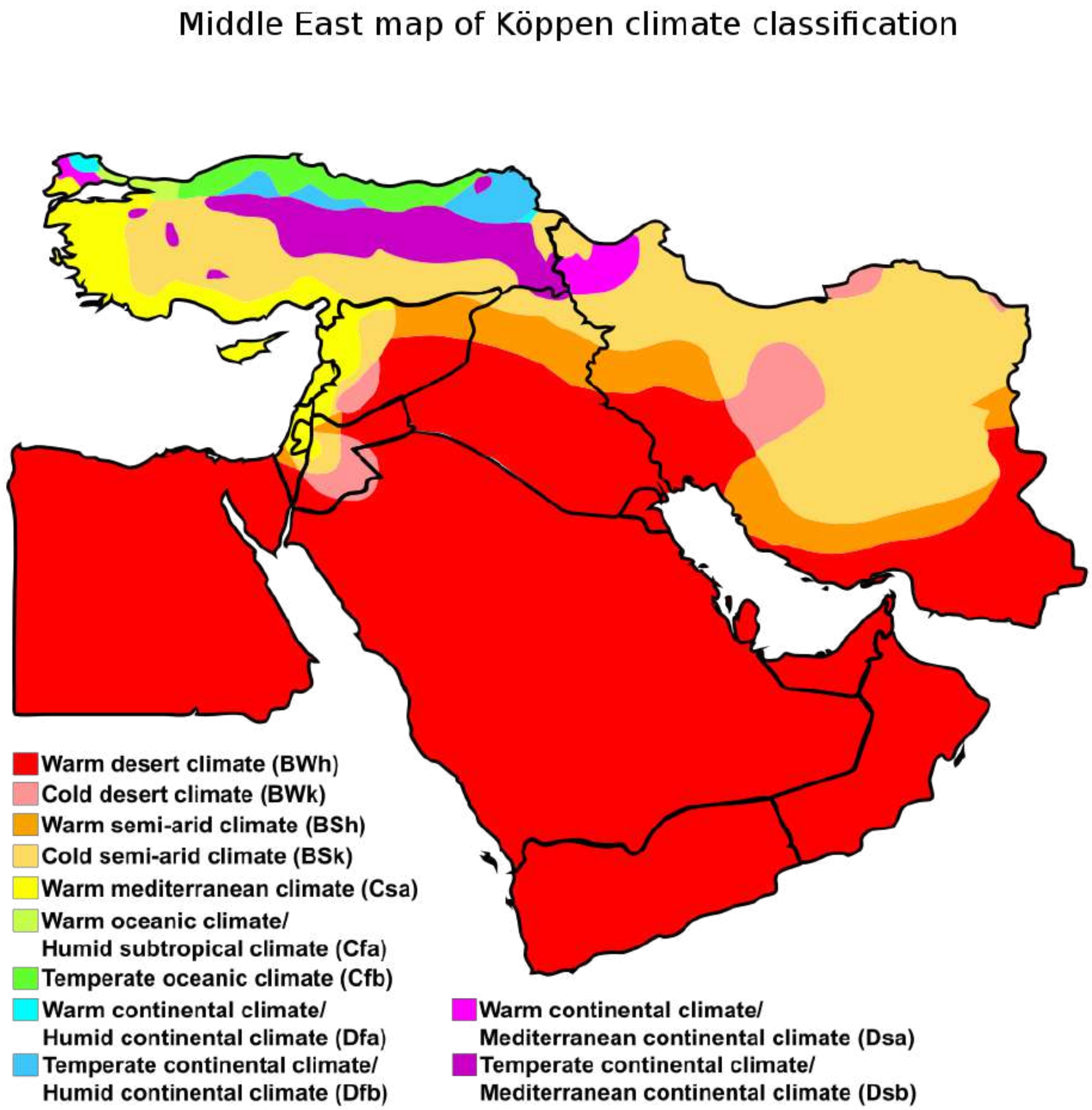

Figure 1.7: **Middle East map of Köppen climate classification.**

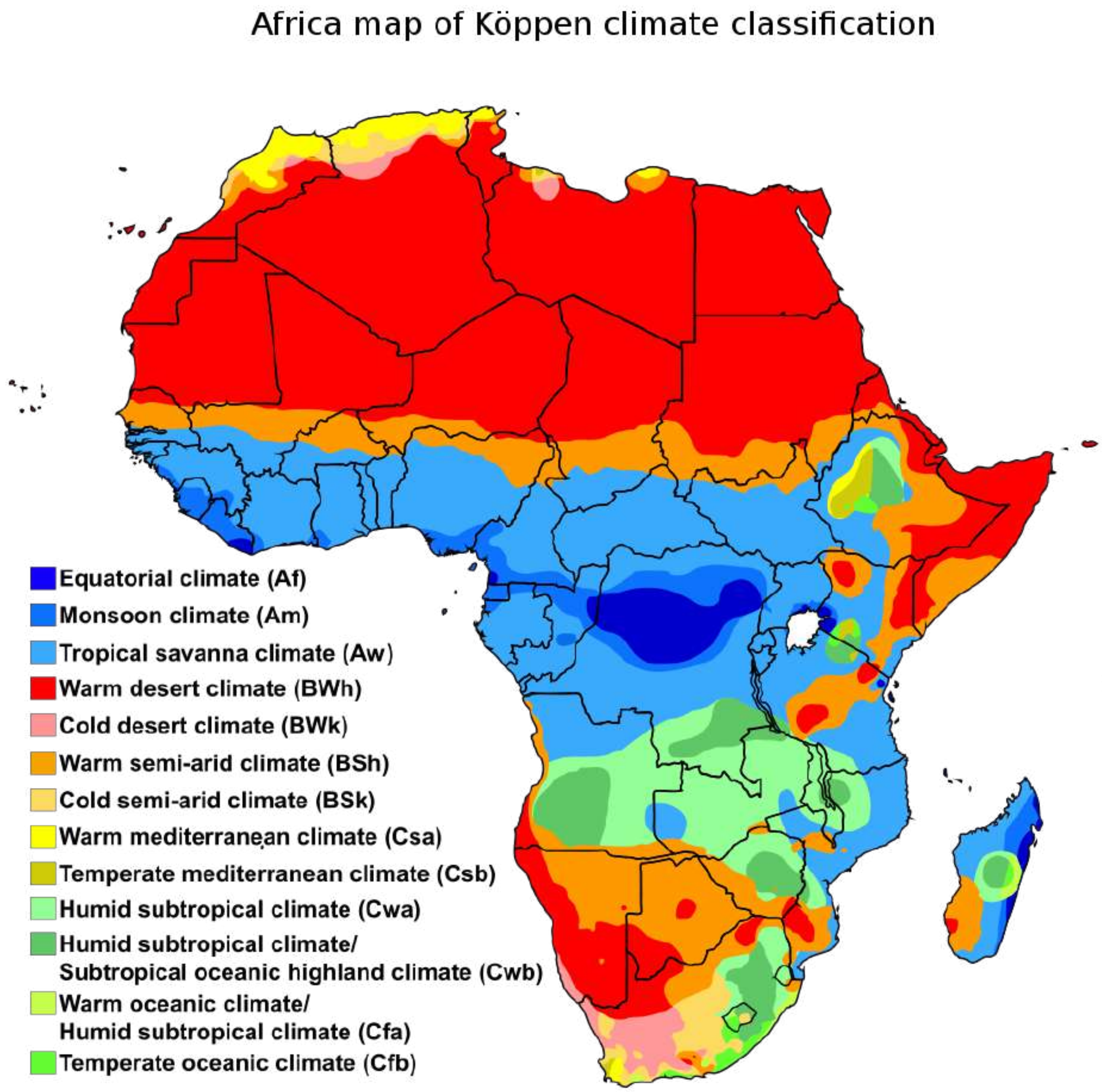

Figure 1.8: **Africa map of Köppen climate classification.**

Figure 1.9: **A Sudanese farmer and his land. Drought and low rainfall has severely reduced the farmer's capacity to grow crops.**

Figure 1.10: **A farmer and his two sons during a dust storm in Cimarron County, Oklahoma, 1936. Photo: Arthur Rothstein.**

1.5 Drought in the Americas

The United States

Today, California and the southwestern states are plagued by drought. The Colorado River is reduced to a trickle when it reaches the Pacific, Water tables are falling. The Ogallala aquifer is overdrawn and disappears as it flows southward. Wildfires caused by extremely dry conditions have hit California and the Pacific Northwest in recent years.

Historically one of the most famous droughts was the one that produced the dust bowl of the 1930's. It led to the displacement of hundreds of thousands of people, as described in John Steinbeck's books, *The Grapes of Wrath* and *Of Mice and Men*.

Central America

Guatemala, El Salvador, Honduras, and Nicaragua are part of an area that has come to be known as the Dry Corridor. It is particularly vulnerable to the effects of climate change and drought because a large percentage of the people in this region live in poverty and are dependent on agriculture, which, in turn, depends on adequate rainfall.

2019 was the fifth consecutive year of drought in the Dry Corridor. Because of failed crops and food insecurity, many people in the region plan to migrate, despite the hardships and risks that this entails.

South America

During the years 2014-2017, Brazil experienced a severe drought, which affected the southeast part of the country, including the cities of Sao Paulo and Rio de Janeiro. Over half the area of Brazil was affected by the drought, which was considered to be the worst in 100 years. The federal government declared a "public calamity" over 6.200 times during these events.

An even worse Brazilian drought, known as the Grande Seca. occurred during the years 1877-1878. This terrible event resulted in the deaths of between 400,000 and 500,000 people.

During the years 1968-1969, a great drought occurred in Chile. All aspects of Chilean agriculture suffered huge losses, including cultivations of potato, rice, maize, beans, fruit trees and vineyards. 100,000 cattle, 400,000 goats and one million sheep died because of lack of water.

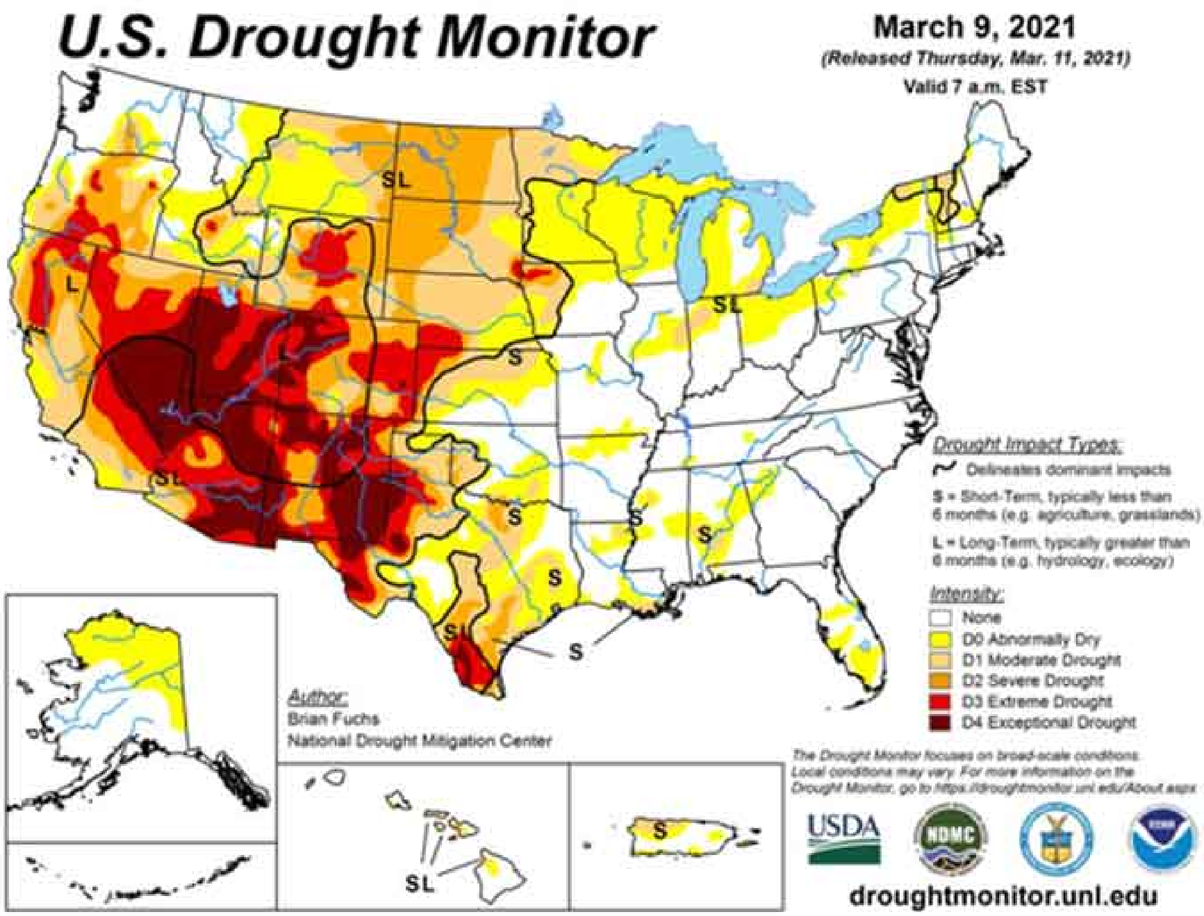

Figure 1.11: **Figure from an article entitled "Worst drought in modern history may hit Western U.S." published in "Countercurrents" on April 12, 2021. The article states that "Extreme drought may be going to hit across the Western U.S. Some scientists saying the region is on the precipice of permanent drought."**

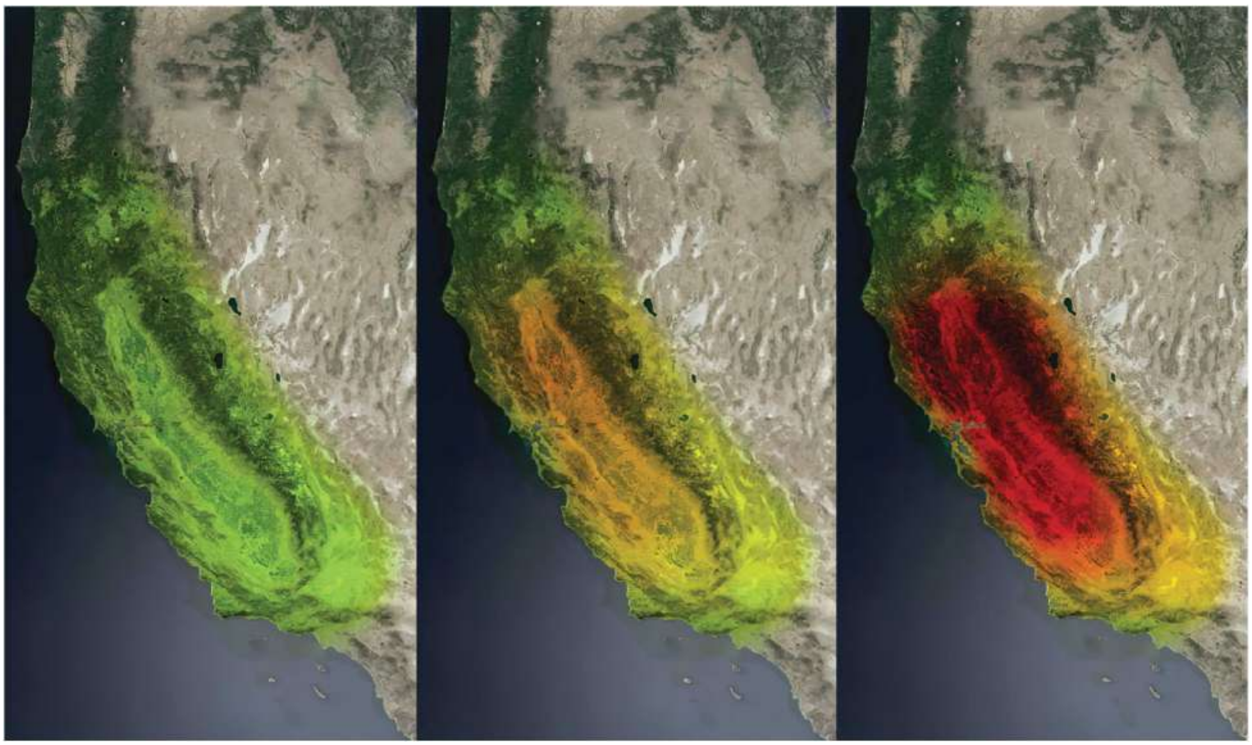

Figure 1.12: **California is drying. NASA's GRACE satellites detect the gravitational pull of water masses in aquifers, reservoirs, and snowpack. In 2014, GRACE data showing water loss (below, red indicates loss) helped dramatize the draining of aquifers and galvanize state lawmakers to protect groundwater. Left to right; June, 2003; June, 2008; and June, 2014**

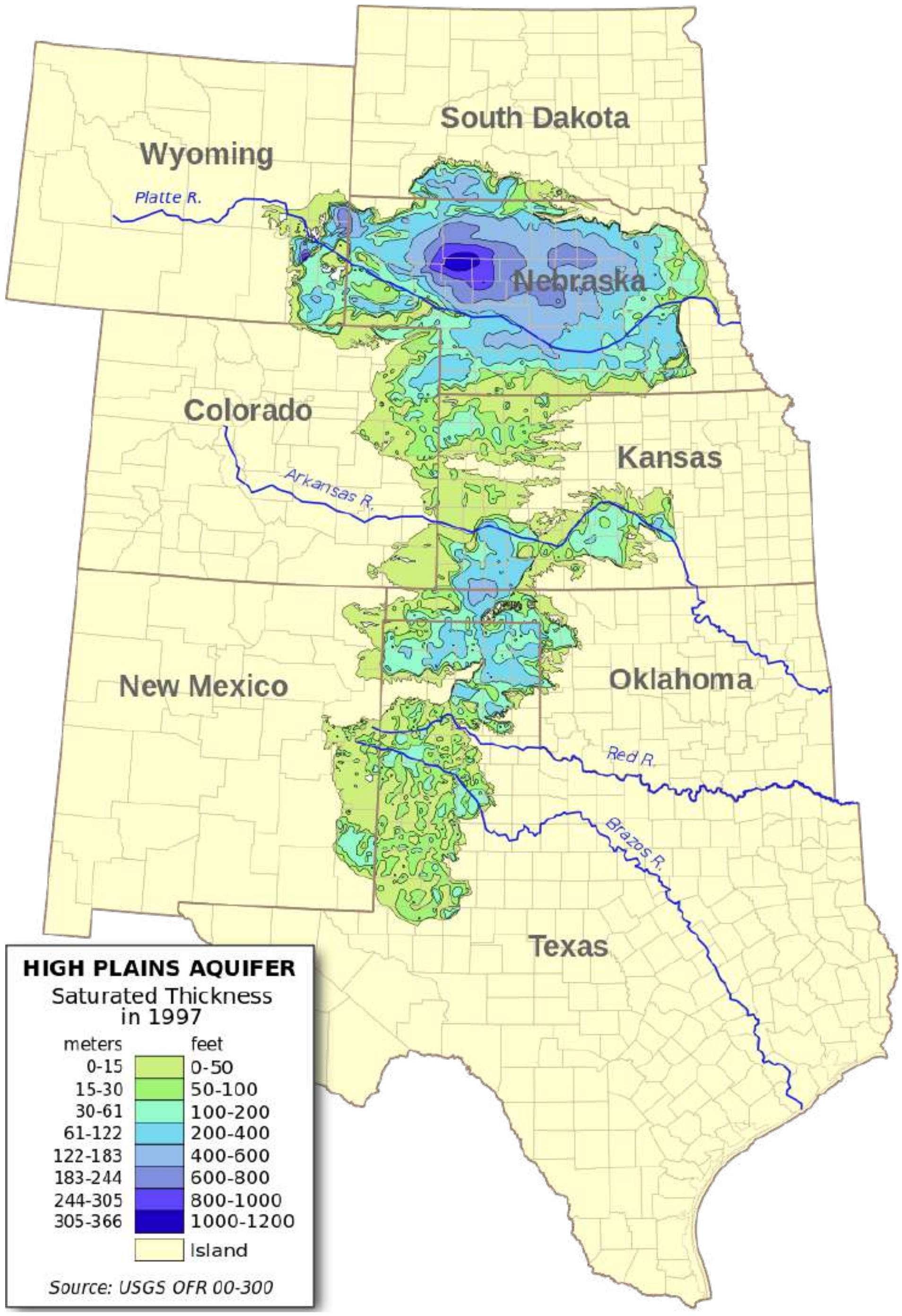

Figure 1.13: **The Ogallala Aquifer has been overdrawn, and can no longer be relied on to irrigate states such as Oklahoma, New Mexico and Texas. The diagram shows the saturated thickness of the Ogallala Aquifer in 1997 after several decades of intensive withdrawals. The breadth and depth of the aquifer generally decrease from north to south.**

Figure 1.14: **The photo shows a farmer in Tabasco State riding past the carcass of a cow which died in the drought. Mexico is enduring its worst drought in six decades. Crops are drying up in the fields and water is being rationed in the capital. Residents of poor neighborhoods have hijacked water trucks, and there are other signs of social tensions building.**

Suggestions for further reading

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Chapter 2

WATER AS A HUMAN RIGHT

2.1 Maude Barlow: water as a human right

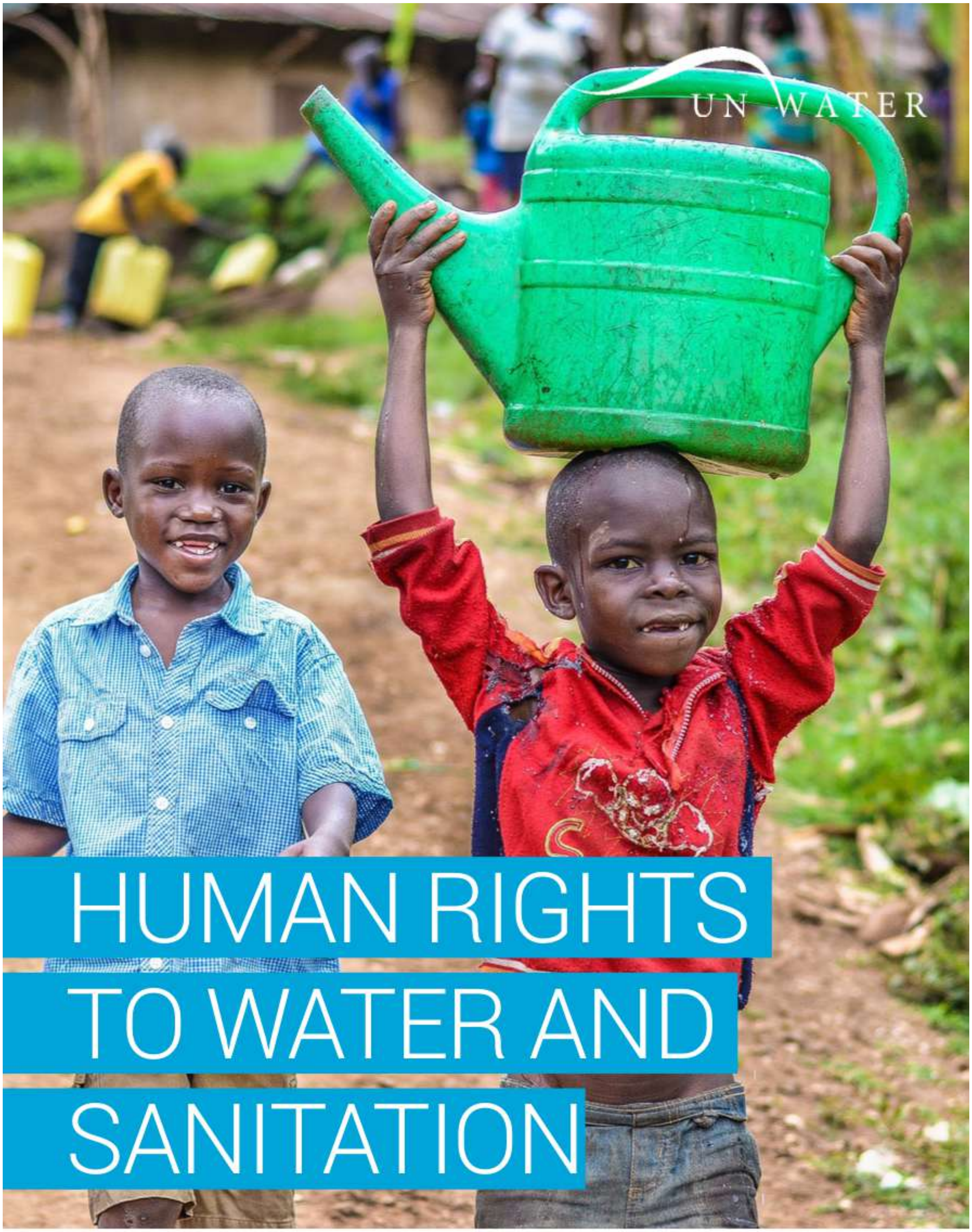
Leader in the struggle against the commodification of water

In many countries, large corporations have taken control of water supplies, and are now selling water at prices that poor citizens cannot afford. Maude Barlow, born in 1947 in Canada, is leading the struggle against the commodification of water. As the result of her campaign, the United Nations has declared water to be a human right. This is particularly important at a time when fresh water is becoming increasingly scarce.

Wikipedia states that "Maude Barlow is the recipient of 12 honorary doctorates as well as many awards, including the 2005 Right Livelihood Award, the Citation of Lifetime Achievement which she received at the 2008 Canadian Environment Awards, the 2009 Earth Day Canada Outstanding Environmental Achievement Award, the 2009 Planet in Focus Eco Hero Award, and the 2011 EarthCare Award, the highest international honour of the Sierra Club (U.S.)."

Books with Maude Barlow as author, co-author or contributor

- *Parcel of Rogues: How Free Trade Is Failing Canada* - Key Porter Books, Toronto (1990)
- *Take Back the Nation* (with Bruce Campbell) - Key Porter Books, Toronto (1992)
- *Take Back the Nation 2* (with Bruce Campbell) - Key Porter Books, Toronto (1993)
- *Class Warfare: The Assault on Canada's Schools* (with Heather-Jane Robertson) - Key Porter Books, Toronto (1994) ISBN 1-55013-559-7.
- *Straight through the Heart: How the Liberals Abandoned the Just Society* (with Bruce Campbell) - Harper Collins, Toronto (1995).
- *The Big Black Book: The Essential Views of Conrad and Barbara Amiel Black* (with Jim Winter) - Stoddart, Toronto (1997).
- MAI: *The Multilateral Agreement on Investment and the Threat to Canadian Sovereignty* (with Tony Clarke) - Stoddart (1997).


UN WATER
HUMAN RIGHTS TO WATER AND SANITATION


UNITED NATIONS

Figure 2.1: **"All people have the right to safe drinking water, sanitation, shelter and basic services." Ban Ki-moon, UN Secretary General.**

Figure 2.2: **Maude Barlow (born 1947). The Wikipedia article on her states that she is a "Canadian author and activist. She is the National Chairperson of the Council of Canadians, a citizens' advocacy organization with members and chapters across Canada. She is also the co-founder of the Blue Planet Project, which works internationally for the human right to water. Maude chairs the board of Washington-based Food and Water Watch, is a founding member of the San Francisco-based International Forum on Globalization, and a Councillor with the Hamburg-based World Future Council. In 2008/2009, she served as Senior Advisor on Water to the 63rd President of the United Nations General Assembly and was a leader in the campaign to have water recognized as a human right by the UN. She has authored and co-authored 16 books." Maude Barlow's work on the issue of water is especially important because fresh water is becoming increasingly scarce throughout the world."**

- MAI: *The Multilateral Agreement on Investment and the Threat to American Freedom* (with Tony Clarke) - Stoddart, Toronto (1998)
- *The Fight of My Life: Confessions of an Unrepentant Canadian* - Harper Collins, Toronto (1998).
- *MAI: The Multilateral Agreement on Investment Round 2; New Global and Internal Threats to Canadian Sovereignty* (with Tony Clarke) - Stoddart, Toronto (1998)
- *Frederick Street: Life and Death on Canada's Love Canal* (with Elizabeth May) - Harper Collins, Toronto (2000)
- *Global Showdown: How the New Activists Are Fighting Global Corporate Rule* (with Tony Clarke) - Stoddart, Toronto (2001).
- *Blue Gold: The Battle Against Corporate Theft of the World's Water* (with Tony Clarke) - Stoddart, Toronto (2002).
- *Profit Is Not the Cure: A Citizen's Guide to Saving Medicare* - McCelland & Stewart, Toronto (2002).
- *Too Close For Comfort; Canada's Future Within Fortress North America* - McClelland & Stewart, Toronto (2005).
- *Blue Covenant: The Global Water Crisis and the Fight for the Right to Water* - McClelland & Stewart, Toronto (October 16, 2007). Also available in French, Arabic, Japanese, Portuguese, Korean, Greek, Turkish, and Spanish.
- *Blue Future: Protecting Water for People and the Planet Forever* - House of Anansi, Inc., Toronto (September 2013).
- *Boiling Point: Government Neglect, Corporate Abuse, and Canada's Water Crisis* - ECW Press, Toronto (September 2016).
- *The Silent Revolution: Media, Democracy, and the Free Trade Debate*. University of Ottawa Press, Ottawa. (1990).
- *Trading Freedom: How Free Trade Affect our Lives, Work, and Environment* - Institute for Policy Studies, Washington (1992)
- *The American Review of Canadian Studies* - Twentieth Anniversary Issue of The Association for Canadian Studies in the United States, Washington (1992)
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- *Whose Water Is It? The Unquenchable Thirst of a Water-Hungry World* - Edited by Bernadette McDonald and Douglas Jehl, National Geographic, Washington (2003)

- *Meeting the Global Challenge: Competitive Position and Strategic Response* - BMA Program, Edited by Tom Wesson, York University Press, Toronto (2004)
- *Globalization, Human Rights & Citizenship, An Anthology From the Gannett Lecture Series* - Rochester Institute of Technology, Edited by Robert Manning - trade paperback (2005)

Reports

- *Blue Gold: The Global Water Crisis and the Commodification of the World's Water Supply* - International Forum on Globalization, San Francisco (June 1999) See also: Commodification of water
- *The Free Trade Area of the Americas, The Threat to Social Programs, Environmental Sustainability and Social Justice* - International Forum on Globalization, San Francisco (February 2001)
- *The World Trade Organization and the Threat to Canada's Social Programs* - The Council of Canadians, Ottawa (September 2001)
- *Profit is not the Cure: A Call to Action on the Future of Health Care in Canada* - The Council of Canadians, Ottawa (Winter 2002)
- *Making the Links, A Citizen's Guide to the World Trade Organization and the Free Trade Area of the Americas* (with Tony Clarke) - The Council of Canadians, Ottawa (Summer 2003)
- *The Global Fight Against Privatization of Water* - Annual Report, The World Forum on Alternatives, Geneva (April 2004)
- *The Canada We Want, A Citizen's Alternative to Deep Integration* - The Council of Canadians, Ottawa (March 2004)

A few things that Maude Barlow has said

Unlimited growth assumes unlimited resources, and this is the genesis of Ecocide.

Do not listen to those who say there is nothing you can do to the very real and large social and environmental issues of our time.

Everything is now for sale. Even those areas of life that we once considered sacred like health and education, food and water and air and seeds and genes and a heritage. It is all now for sale.

There is simply no way to overstate the water crisis of the planet today.

We are committed with our lives to building a different model and a different future for humanity, the Earth, and other species. We have envisaged a

moral alternative to economic globalization and we will not rest until we see it realized.

The destruction of aquatic ecosystem health, and the increasing water scarcity, are in my opinion the most pressing environmental problems facing human kind.

No piecemeal solution is going to prevent the collapse of whole societies and ecosystems ... a radical re-thinking of our values, priorities and political systems is urgent.

At the heart of the WTO is an assault on everything left standing in the commons, in the public realm. Everything is now for sale. Even those areas of life that we once considered sacred like health and education, food and water and air and seeds and genes and a heritage. It is all now for sale. Economic freedom - not democracy, and not ecological stewardship - is the defining metaphor of the WTO and its central goal is humanity's mastery of the natural world through its total commodification.

Robert Glennon is a leading-edge legal scholar and passionate water advocate whose thinking is central to an intense debate on the path forward to a water-secure world. I heartily recommend his provocative, information-packed, and highly readable new book Unquenchable.

2.2 The global water crisis

Falling water tables in China may cause famine in Africa

After a lecture at the University of Copenhagen in the 1980's, Lester R. Brown of the Earth Policy Institute was asked which resource would be the first to become critically scarce. Everyone in the audience expected him to say "oil", but instead he said "fresh water". He went on to explain that falling water tables in China would soon make China unable to feed its population. This would not cause famine in China itself because of the strength of the Chinese economy, which would allow the Chinese to purchase grain on the world market. However, shortages of fresh water in China would indeed cause famine, for example in Africa, because Chinese demand for grain would raise prices on the world market beyond the ability of poor countries to pay.

Predictions of drought in the Stern Review

According to a report presented to the Oxford Institute of Economic Policy by Sir Nicholas Stern on 31 January, 2006, areas likely to lose up to 30% of their rainfall by the 2050's

Figure 2.3: **Lester R. Brown: "Water will be the most critical resource."**

because of climate change include much of the United States, Brazil, the Mediterranean region, Eastern Russia and Belarus, the Middle East, Southern Africa and Southern Australia. Meanwhile rainfall is predicted to increase up to 30% in Central Africa, Pakistan, India, Bangladesh, Siberia, and much of China.

Stern and his team point out that "We can... expect to see changes in the Indian monsoon, which could have a huge impact on the lives of hundreds of millions of people in India, Pakistan and Bangladesh. Most climate models suggest that the monsoon will change, although there is still uncertainty about exactly how. Nevertheless, small changes in the monsoon could have a huge impact. Today, a fluctuation of just 10% in either direction from average monsoon rainfall is known to cause either severe flooding or drought. A weak summer monsoon, for example, can lead to poor harvests and food shortages among the rural population - two-thirds of India's almost 1.1 billion people. Heavier-than-usual monsoon downpours can also have devastating consequences..."

In some regions, melting of glaciers can be serious from the standpoint of dry-season water supplies. For example, melts from glaciers in the Hindu Kush and the Himalayas now supply much of Asia, including China and India, with a dry-season water supply. Complete melting of these glacial systems would cause an exaggerated runoff for a few decades, after which there would be a drying out of some of the most densely populated regions of the world.

Ocean current changes and failure of monsoons

It is expected that climate change will affect ocean currents, and hence also affect monsoon rainfall. We are already experiencing a diversion of the Gulf Stream due to southward currents of cold water from melting ice in the Arctic. This has caused what is known as the *North Atlantic Anomaly*. While most regions of the world are experiencing rising temperatures, the North Atlantic and several northern European countries are exceptions to this rule, and have cooled. Complete failure of the Gulf Stream would lead to much colder temperatures in Europe.

Changes in ocean currents have already lead to the failure of the West African Monsoon, and this has already produced severe food insecurity in West Africa.

In the future, climate-changed ocean currents may lead to failures of monsoons in South-east Asia, and thus damage the food supply of almost two billion people.

Falling water tables around the world

Under many desert areas of the world are deeply buried water tables formed during glacial periods when the climate of these regions was wetter. These regions include the Middle East and large parts of Africa. Water can be withdrawn from such ancient reservoirs by deep wells and pumping, but only for a limited amount of time.

In oil-rich Saudi Arabia, petroenergy is used to drill wells for ancient water and to bring it to the surface. Much of this water is used to irrigate wheat fields, and this is done to such an extent that Saudi Arabia exports wheat. The country is, in effect, exporting its ancient heritage of water, a policy that it may, in time, regret. A similarly short-sighted project is Muammar Qaddafi's enormous pipeline, which will bring water from ancient sub-desert reservoirs to coastal cities.

In the United States, the great Ogallala aquifer is being overdrawn. This aquifer is an enormous stratum of water-saturated sand and gravel under-lying parts of northern Texas, Oklahoma, New Mexico, Kansas, Colorado, Nebraska, Wyoming and South Dakota. The average thickness of the aquifer is about 70 meters. The rate of water withdrawal from the aquifer exceeds the rate of recharge by a factor of eight.

Thus we can see that in many regions, the earth's present population is living on its inheritance of water, rather than its income. This fact, coupled with rapidly increasing populations and climate change, may contribute to a very serious food crisis partway through the 21st century.

Glacial melting and summer water supplies

The summer water supplies of both China and India are threatened by the melting of glaciers. The Gangotri glacier, which is the principle glacier feeding India's great Ganges River, is reported to be melting at an accelerating rate, and it could disappear within a few decades. If this happens,the Ganges could become seasonal, flowing only during the monsoon season. Chinese agriculture is also threatened by disappearing Himalayan glaciers, in this case those on the Tibet-Quinghai Plateau. The respected Chinese glaciologist Yao Tandong estimates that the glaciers feeding the Yangtze and Yellow Rivers are disappearing at the rate of 7% per year.[1]

[1] http://www.commondreams.org/news/2015/08/04/global-glaciers-melting-three-times-rate-20th-century

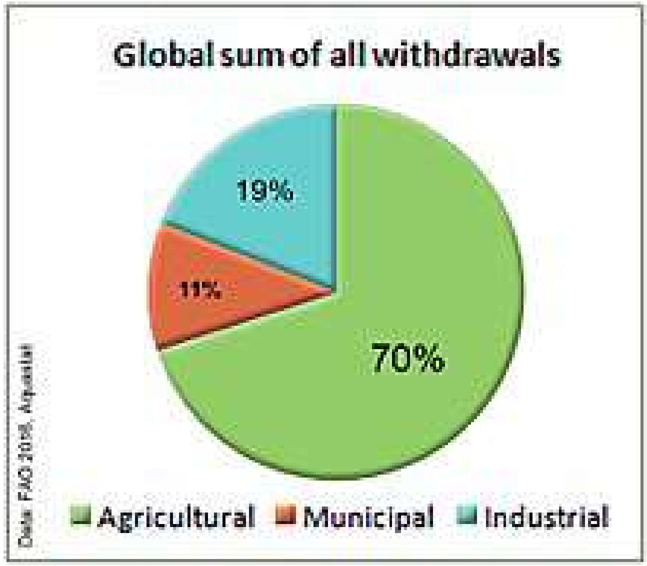


Figure 2.4: **Global use of fresh water (FAO data).**

How many people are currently under stress?

It is estimated that two thirds of the world's peoples currently live under water stress for at least one month each year. Half a billion people now suffer from water shortages and stress for the entire year. Half of the world's large cities are currently plagued by water scarcity, and the situation is expected to get worse.

Dangers from water wars

Water plays a role in present conflicts, for example in the conflict between the government of Israel and the country's Palestinian population. In the future, there may be many other conflicts over water, for example between China and India. China is building a canal to take water from the Tibetan Plateau to Beijing, thus reducing the amount of water in rivers flowing down from the plateau into India. Other dangerous water conflicts loom in regions such as Sudan.

Advances in desalination technology

Scientists at the Massachusetts Institute of Technology have developed a new desalination process, called shock electrodialysis. In this process. water flows through a porous material -in this case, made of tiny glass particles, called a frit - with membranes or electrodes sandwiching the porous material on each side. When an electric current flows through the system, the salty water divides into regions where the salt concentration is either depleted or enriched. When that current is increased to a certain point, it generates a shockwave between these two zones, sharply dividing the streams and allowing the fresh and salty

Figure 2.5: **In Meatu district, Simiyu Region, Tanzania (Africa), water most often comes from open holes dug in the sand of dry riverbeds, and it is invariably contaminated. Many children are deprived of an education primarily due to this daily task.**

Figure 2.6: **Deforestation of the Madagascar Highland Plateau has led to extensive siltation and unstable flows of western rivers.**

Figure 2.7: **A South Asian woman carrying water on her head, 2016.**

regions to be separated by a simple physical barrier at the center of the flow.

"It generates a very strong gradient," says Martin Bazant, a researcher involved with the project[2].

Even though the system can use membranes on each side of the porous material, Bazant explains, the water flows across those membranes, not through them. That means they are not as vulnerable to fouling - a buildup of filtered material - or to degradation due to water pressure, as happens with conventional membrane-based desalination, including conventional electrodialysis. "The salt doesn't have to push through something," Bazant says. "The charged salt particles, or ions, just move to one side".

2.3 Water on Wall Street

With two billion people already living in water-stressed areas of the world, and most of the world's population projected to be water-stressed by 2050, water is becoming a very critical resource. Now. as California emerges from a seven year drought, and as wildfires ravage the Pacific coast, CME, a Chicago-based company with ties to the California water market has announced a scheme under which speculators can bet on the future price of water.

But is water a human tight, as Maude Barlow and the United Nations have proclaimed? Or is it just another commodity on which speculators can bet for their own enrichment?

[2] He was quoted in an article published in *MIT News*, November 12, 2015

Figure 2.8: **The photo shows Wall Street water traders. Water shortages could affect around five billion people worldwide by 2050, according to the UN.**

Figure 2.9: **In a first, water has officially joined the likes of gold and oil in being traded on Wall Street as a Futures commodity.**

2.4 Privatization and unaffordable water

Tear gas and bullets in Bolivia

Here are some quotations from an article by Paul Harris published in SEGATE[3]

"In a Goliath-versus-David face-off, Bechtel Group of San Francisco, the largest private company in the Bay Area, is taking legal action against the government of Bolivia, one of the poorest countries in the hemisphere.

"The construction and engineering conglomerate wants $25 million in compensation from Bolivia for canceling a water contract with Cochabamba, the nation's third-largest city.

"The conflict began two years ago when thousands of residents poured into the streets of the city to protest hefty price increases by the local water company, which is a subsidiary of Bechtel.

"After clashes with soldiers firing tear gas and bullets left a 17-year-old protester dead, hundreds injured and more than a dozen protest leaders in jail, Bolivia's government suspended its 40-year lease with the company.

"Bechtel now demands compensation for the canceled contract. An arbitration board sponsored by the World Bank is expected to decide within the next few weeks whether to consider the case.

"Since Bechtel is one of the most powerful corporations in the world – with $14.3 billion in revenue in 2000 – some critics have suggested that it should merely absorb its losses rather than exact payment from impoverished Bolivia, whose national budget is only $2.7 billion, compared with $642 billion for last year's U.S. budget.

"Others say the legal imbroglio is a symbol of globalization run amok.

" 'These investment treaties (such as trade pacts and privatization) make the profits of multinational corporations more important than the basic rights of people,' said Joshua Karliner, executive director of CorpWatch in San Francisco, a watchdog group that tracks corporate behavior worldwide."

A dangerous corporate monopoly

Here is a quotation from an article by Kenny Stancel, published on April 12, 2021 in *Common Dreams*:

"French-based transnational corporation Veolia agreed in principle to acquire Suez, its main rival, for $15.5 billion on Monday, setting the stage for the creation of a water and waste management juggernaut that critics warn would be a 'dangerous corporate monopoly' destined to 'hurt consumers and enrich shareholders.'

[3]https://www.sfgate.com/news/article/Bechtel-battles-against-dirt-poor-Bolivia-2878502.php

"The Wall Street Journal characterized the deal between the two largest private water corporations in the world, which is not expected to be finalized until May 14, as a profit-seeking attempt to 'soak up a global surge in infrastructure and climate-change spending.'

"But progressives say the consolidation of corporate power in the for-profit water industry threatens to further intensify the commodification and privatization of one of the world's most precious resources.

" 'Veolia's plan to dominate public water services all across the globe is becoming a terrifying reality,' Mary Grant, the director of Food & Water Watch's Public Water for All campaign, said in a statement. 'The merger of the world's largest water corporations will erode any semblance of competition for water privatization deals. This lack of competition will worsen our water affordability crisis, eliminate good union jobs, and open the door to cronyism and corruption.'

" 'Water privatization,' Grant continued, 'has been a disaster for communities across the United States and around the world.'

"According to the international watchdog group Corporate Accountability, both Suez and Veolia 'have a long track record of human rights, labor, and environmental abuses' throughout the world."

2.5 The Flint water scandal

In 2014 a public health crisis occurred in the city of Flint, Michigan, when Flint's drinking water was found to be contaminated with lead, and possibly also with legionella bacteria. Children are especially vulnerable to the effects of lead poisoning, and it can lead to lowered intelligence and increased risk of Alzheimer's disease.

In April, 2014, because of a budget crisis, Flint changed its water supply from Lake Huron to the Detroit River. Residents complained about the taste and smell of the new water, but their complaints went unheard. The crisis had a racial dimension, since Flint is a predominantly non-white community.

Finally, in 2015, after two years, both the state of Michigan and Barak Obama's federal government declared a state of emergency, and aid was made available to solve the crisis.

2.6 Hormone analogues in drinking water

Endocrine disruptors in drinking water have been observed in many countries. They are especially worrying because they can cause reproductive disorders. such as lowered fertility and lowered sperm count both in humans and in animals.

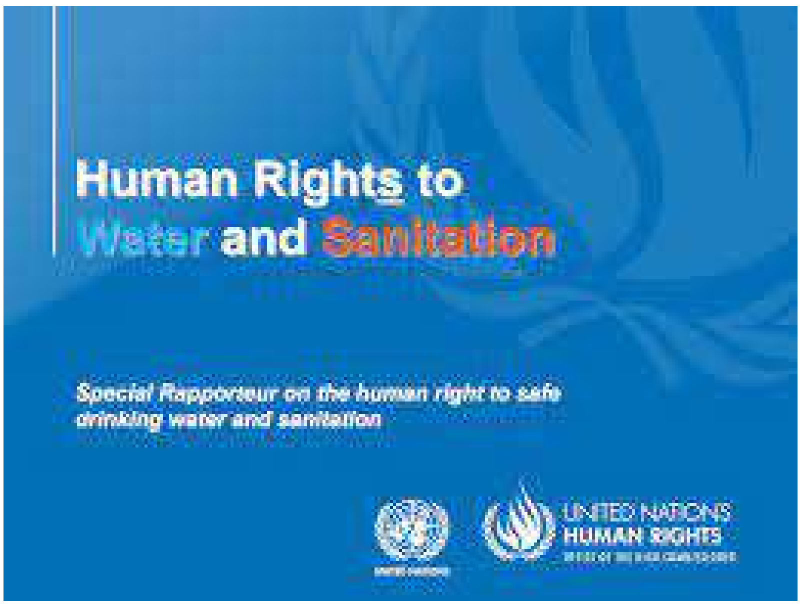
Among the endocrine disruptors found in drinking water are chemicals used in plastic packaging and plastic bottles. Other disruptors may come from the chemicals used to de-contaminate the water.

2.7 Chemicals from fracking in drinking water

Wikipedia makes the following statement in its article on “Environmental impact of hydraulic fracking”:

“Hydraulic fracturing fluids include proppants and other substances, which may include toxic chemicals. In the United States, such additives may be treated as trade secrets by companies who use them. Lack of knowledge about specific chemicals has complicated efforts to develop risk management policies and to study health effects. In other jurisdictions, such as the United Kingdom, these chemicals must be made public and their applications are required to be nonhazardous.

“Water usage by hydraulic fracturing can be a problem in areas that experience water shortage. Surface water may be contaminated through spillage and improperly built and maintained waste pits, in jurisdictions where these are permitted. Further, ground water can be contaminated if fracturing fluids and formation fluids are able to escape during hydraulic fracturing. However, the possibility of groundwater contamination from the fracturing fluid upward migration is negligible, even in a long-term period. Produced water, the water that returns to the surface after hydraulic fracturing, is managed by underground injection, municipal and commercial wastewater treatment, and reuse in future wells. There is potential for methane to leak into ground water and the air, though escape of methane is a bigger problem in older wells than in those built under more recent legislation.”


Human Rights to
Water and Sanitation
Special Rapporteur on the human right to safe
drinking water and sanitation
UNITED NATIONS
HUMAN RIGHTS

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Chapter 3

WATER, CLIMATE CHANGE AND WILDFIRES

3.1 Global warming and atmospheric water vapor

A feedback loop is a self-re-enforcing trend. One of the main positive feedback loops in global warming is the tendency of warming to increase the atmospheric saturation pressure for water vapor, and hence amount of water vapor in the atmosphere, which in turn leads to further warming, since water vapor is a greenhouse gas.

Wikipedia's article on greenhouse gases states that, "Water vapor accounts for the largest percentage of the greenhouse effect, between 36% and 66% for clear sky conditions and between 66% and 85% when including clouds."

3.2 The albedo effect

Albedo is defined to be the fraction of solar energy (shortwave radiation) reflected from the Earth back into space. It is a measure of the reflectivity of the earth's surface. Ice, especially with snow on top of it, has a high albedo: most sunlight hitting the surface bounces back towards space.

Loss of sea ice

Especially in the Arctic and Antarctic regions, there exists a dangerous feedback loop involving the albedo of ice and snow. Arctic sea ice is rapidly disappearing. It is predicted that during the summers, the ice covering arctic seas may disappear entirely. As a consequence, incoming sunlight will encounter dark light-absorbing water surfaces rather than light-reflecting ice and snow.

This effect is self-re-enforcing. In other words, it is a feedback loop. The rising temperatures caused by the absorption of more solar radiation cause the melting of more ice, and hence even more absorption of radiation rather than reflection, still higher temperatures, more melting, and so on.

The feedback loop is further strengthened by the fact that water vapor acts as a greenhouse gas. As polar oceans become exposed, more water vapor enters the atmosphere, where it contributes to the greenhouse effect and rising temperatures.

Darkened snow on Greenland's icecap

Greenland's icecap is melting, and as it melts, the surface becomes darker and less reflective because particles of soot previously trapped in the snow and ice become exposed. This darkened surface absorbs an increased amount of solar radiation, and the result is accelerated melting.

3.3 The methane hydrate feedback loop

If we look at the distant future, by far the most dangerous feedback loop involves methane hydrates or methane clathrates. When organic matter is carried into the oceans by rivers, it decays to form methane. The methane then combines with water to form hydrate crystals, which are stable at the temperatures and pressures which currently exist on ocean floors. However, if the temperature rises, the crystals become unstable, and methane gas bubbles up to the surface. Methane is a greenhouse gas which is 70 times as potent as CO_2.

The worrying thing about the methane hydrate deposits on ocean floors is the enormous amount of carbon involved: roughly 10,000 gigatons. To put this huge amount into perspective, we can remember that the total amount of carbon in world CO_2 emissions since 1751 has only been 337 gigatons.

A runaway, exponentially increasing, feedback loop involving methane hydrates could lead to one of the great geological extinction events that have periodically wiped out most of the animals and plants then living. This must be avoided at all costs.

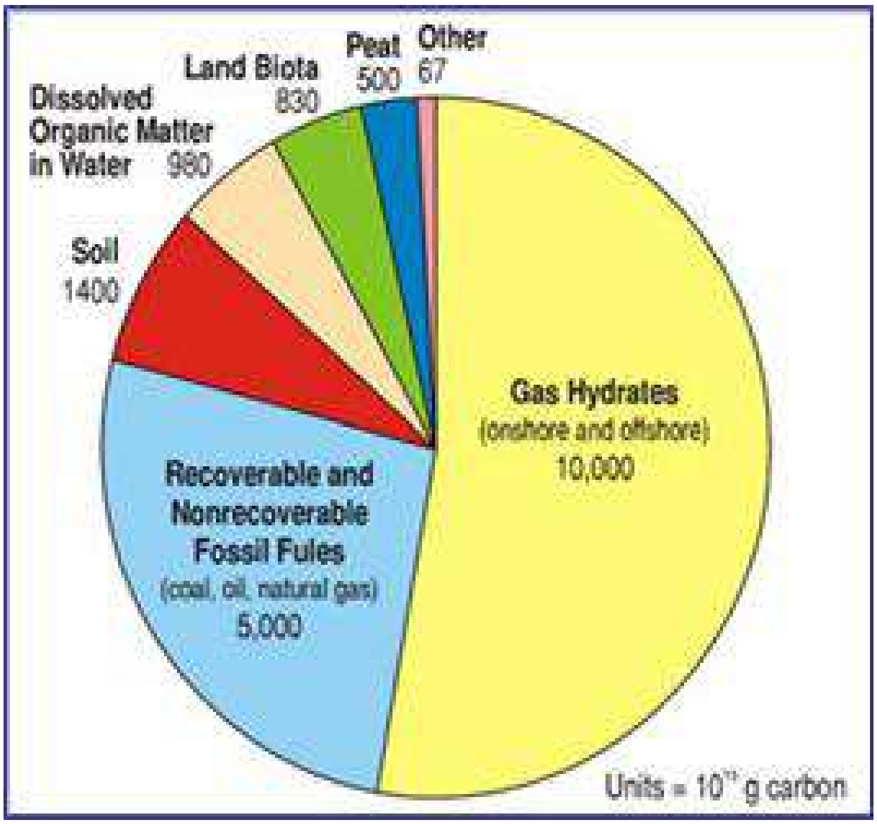

Figure 3.1: **The worrying thing about the methane/hydrate feedback loop is the enormous amount of carbon in the form of hydrate crystals, 10,000 gigatons, most of it on the continental shelves of oceans. This greater than the amount of carbon in all other forms that might potentially enter the earth's atmosphere.**

Figure 3.2: **When ocean temperatures rise, methane hydrate crystals become unstable, and methane gas bubbles up to ocean surfaces.**

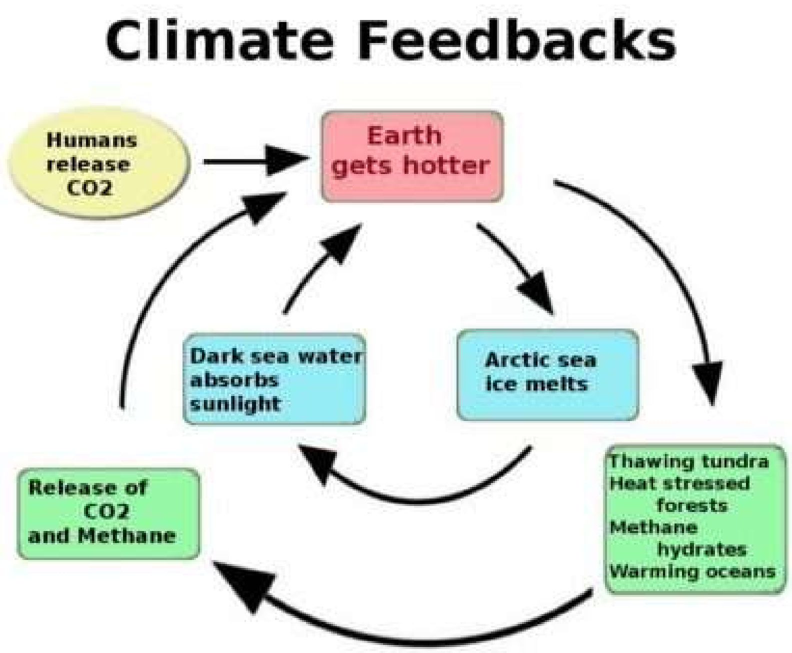

Figure 3.3: **This diagram shows two important feedback loops, one involving the albedo effect, and the other involving methane hydrates.**

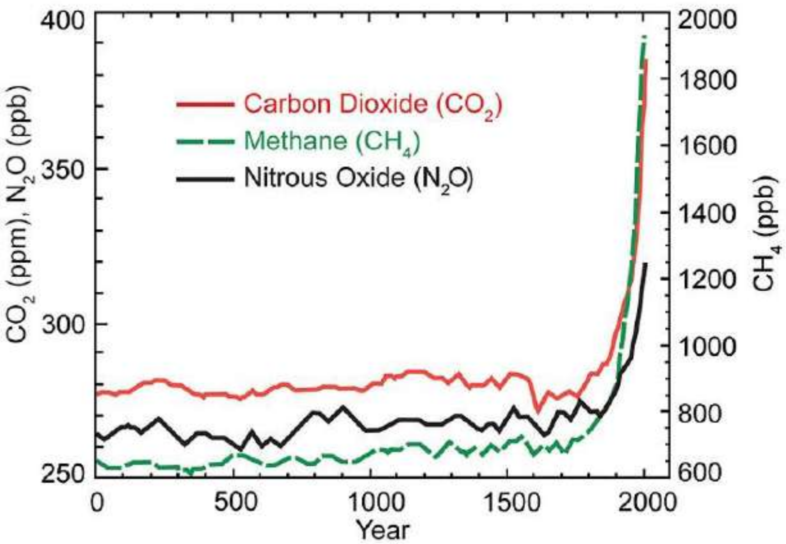

Figure 3.4: **A "hockey stick" graph showing atmospheric concentrations of three important greenhouse gasses during the last 2,000 years. The most dramatically increasing of these is methane.**

3.4 A feedback loop from warming of soils

On October 6, 2017, the journal *Science* published an article entitled *Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world*[1]. The lead author, Jerry Melillo, is an ecologist working at the Marine Biological Laboratory, Woods Hole Massachusetts. In an interview with *Newsweek*, he said: "This self-reinforcing feedback is potentially a global phenomenon with soils, and once it starts it may be very difficult to turn off. It's that part of the problem that I think is sobering... We think that one of the things that may be happening is both a reorganization of the microbial community structure and its functional capacity,"

The study reported on three decades of observations of heated sections of a forest owned by Harvard University. The heated sections were 5^{o}C warmer than control sections.

3.5 Drying of forests and forest fires

According to a recent article in *Nature*[2],"Across the American west, the area burned each year has increased significantly over the past several decades, a trend that scientists attribute both to warming and drying and to a century of wildfire suppression and other human activities. Allen suggests that the intertwined forces of fire and climate change

[1]J.M. Melillo et al., *Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world*, Science, Vol. 358, pp. 101-105, (2017).

[2]http://www.nature.com/news/forest-fires-burn-out-1.11424

Figure 3.5: **Fighting a fire in California, caused by the unusually hot and dry weather of the summer of 2018. The very dry weather also caused uncontrollable fires in the Arctic, in Sweden, Russia, Northern Canada and Alaska.**

will take ecosystems into new territory, not only in the American west but also elsewhere around the world. In the Jemez, for example, it could transform much of the ponderosa pine (Pinus ponderosa) forest into shrub land. 'We're losing forests as we've known them for a very long time,' says Allen. 'We're on a different trajectory, and we're not yet sure where we're going.'

"All around the American west, scientists are seeing signs that fire and climate change are combining to create a 'new normal'. Ten years after Colorado's largest recorded fire burned 56,000 hectares southwest of Denver, the forest still has not rebounded in a 20,000-hectare patch in the middle, which was devastated by an intense crown fire. Only a few thousand hectares, which the US Forest Service replanted, look anything like the ponderosa-pine stands that previously dominated the landscape."

Figure 3.6: **Over two million acres have burned in the state this year alone, as California faces the worst fires in its history. This photo shows the Creek Fire as it burns along a hillside in the Cascadel Woods community of Madera County.**

Figure 3.7: **The Rim Fire burned more than 250,000 acres (1,000 km2) of forest near Yosemite National Park, in 2013.**

Figure 3.8: **Lightning-sparked wildfires are frequent occurrences during the dry summer season in Nevada.**

Figure 3.9: **A wildfire in Venezuela during a drought.**

Figure 3.10: **"Elk Bath", an award winning photograph of elk avoiding a wildfire in Montana.**

Figure 3.11: **A fire engine from the Idanha-Detroit Rural Fire Protection District sits on Detroit Avenue Friday, Sept. 11, 2020, in Detroit, Oregon. The engine was destroyed on Wednesday when the Lionshead Fire over-ran the resort community of Detroit, merging with the Beachie Creek Fire. Only the post office and a market survived the fire in the town's business district.**

Figure 3.12: **Bush fires in Australia threatened Sydney and caused the Australian government to declare a state of emergency. But Australia's politicians continue the policies that have made their nation a climate change criminal, exporting vast quantities of coal and beef. The Deputy Prime Minister Michael McCormack said, of the fire victems: "They don't need the ravings of some pure enlightened and woke capital city greenies at this time when they are trying to save their homes." In other words, let's not talk about climate change.**

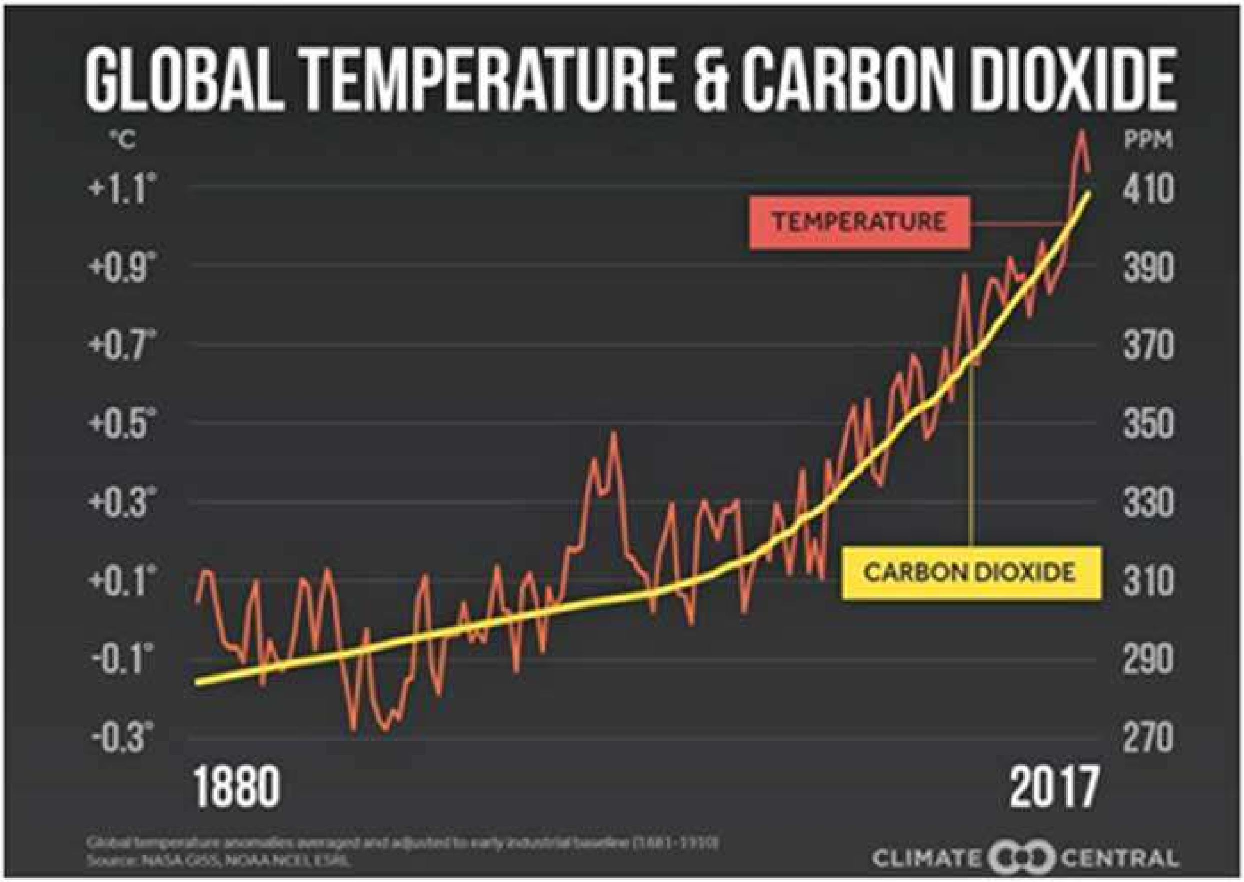

Figure 3.13: **The graphs showing increase in global temperatures and carbon dioxide follow each other closely. In an article published in Countercurrents on November 6, 2019, Dr. Andrew Glickson wrote: "As the concentration of atmospheric CO_2 has risen to 408 ppm and the total greenhouse gas level, including methane and nitrous oxide, combine to near 500 parts per million CO_2-equivalent, the stability threshold of the Greenland and Antarctic ice sheets, currently melting at an accelerated rate, has been exceeded. The consequent expansion of tropics and the shift of climate zones toward the shrinking poles lead to increasingly warm and dry conditions under which fire storms, currently engulfing large parts of South America, California, Alaska, Siberia, Sweden, Spain, Portugal, Greece, Angola, Australia and elsewhere have become a dominant factor in the destruction of terrestrial habitats."**

Figure 3.14: **The Royal Society of the United Kingdom documented ExxonMobil's funding of 39 organizations that promoted "inaccurate and misleading" views of climate science. In an article published by TomDispatch on November 11. 2019, Professor Naomi Oreskes of Harvard University wrote: "Much focus has been put on ExxonMobil's history of disseminating disinformation, partly because of the documented discrepancies between what that company said in public about climate change and what its officials said (and funded) in private. Recently, a trial began in New York City accusing the company of misleading its investors, while Massachusetts is prosecuting ExxonMobil for misleading consumers as well. If only it had just been that one company, but for more than 30 years, the fossil-fuel industry and its allies have denied the truth about anthropogenic global warming. They have systematically misled the American people and so purposely contributed to endless delays in dealing with the issue by, among other things, discounting and disparaging climate science, mispresenting scientific findings, and attempting to discredit climate scientists. These activities are documented in great detail in *How Americans Were Deliberately Misled about Climate Change*, a report I recently co-authored, as well as in my 2010 book and 2014 film, *Merchants of Doubt.*"**

3.6 Tipping points and feedback loops

A tipping point is usually defined as the threshold for an abrupt and irreversible change[3]. To illustrate this idea, we can think of a book lying on a table. If we gradually push the book towards the edge of the table, we will finally reach a point after which more than half of the weight of the book will not be not supported by the table. When this "tipping point" is passed the situation will suddenly become unstable, and the book will fall to the floor. Analogously, as the earth's climate gradually changes, we may reach tipping points. If we pass these points, sudden instabilities and abrupt climatic changes will occur.

Greenland ice cores supply a record of temperatures in the past, and through geological evidence we have evidence of sea levels in past epochs. These historical records show that abrupt climatic changes have occurred in the past.

Timothy Michael Lenton, FRS, Professor of Climate Change and Earth System Science at he University of Exeter, lists the following examples of climatic tipping points:

- Boreal forest dieback
- Amazon rainforest dieback
- Loss of Arctic and Antarctic sea ice (Polar ice packs) and melting of Greenland and Antarctic ice sheets
- Disruption to Indian and West African monsoon
- Formation of Atlantic deep water near the Arctic ocean, which is a component process of the thermohaline circulation.
- Loss of permafrost, leading to potential Arctic methane release and clathrate gun effect

It can be seen from this list that climate tipping points are associated with feedback loops. For example, the boreal forest dieback and the Amazon rainforest dieback tipping points are associated with the feedback loop involving the drying of forests and forest fires, while the tipping point involving loss of Arctic and Antarctic sea ice is associated with the Albedo effect feedback loop. The tipping point involving loss of permafrost is associated with the methane hydrate feedback loop.

Once a positive feedback loop starts to operate in earnest, change may be abrupt.

[3]Other definitions of tipping points are possible. A few authors define these as points beyond which change is inevitable, emphasizing that while inevitable, the change may be slow.

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Chapter 4

FLOODS

4.1 Religious legends of an ancient flood

The Black Sea Deluge hypothesis

The story of a great flood that covered the whole earth occurs not only in the Hebrew Bible but also in other writings, for example the Mesopotamian Gilgamish Epic.

Do these myths have any basis in reality? Of course it is impossible for a flood to cover the whole earth, but floods can be very large and catastrophic. A number of explanations have been proposed for the religious flood myths of the Middle East. One of these is the controversial Black Sea Deluge hypothesis.

According to this hypothesis, first put forward in 1997 by William Ryan and Walter Pitman, the Black Sea was a relatively small freshwater lake before the great flood occurred. The Bosporos Strait, which currently allows water from the Mediterranean to reach the Black Sea basin, was above sea level, so the flow of water was blocked. Humans settled on the shores of the fresh water lake in what is now the Black Sea.

Then sea levels rose to such an extent that large volumes water from the Mediterranean began to flow over the Bosporus Strait, catastrophically drowning human settlements. Support for this controversial hypothesis has come recently from the discovery of evidence of human habitation on the floor of the Black Sea.

Evidence for flooding at Ur and Kish in Mesopotamia

During the years 1928-1928, within a few months of each other, archaeologists digging at the southern Mesopotamian sites of Ur and Kish announced that they had found evidence of an ancient flood. However, careful dating of artefacts discovered at the two digs showed that it was not the same flood.

The dig at Ur was conducted by the famous archaeologist, Sir Charles Leonard Woolley. After studying the royal tombs at Ur, Woolley had a deep test shaft dug. He found that it passed through eight feet of bare mud before encountering a layer containing prehistoric human artifacts. Woolley later wrote: "...by the time I had written up my notes was quite

Figure 4.1: **A woodcut of Noah's Ark from Anton Koberger's German Bible.**

convinced of what it all meant; but I wanted to see whether others would come to the same conclusion. So I brought up two of my staff and, after pointing out the facts, asked for their explanation. They did not know what to say. My wife came along and looked and was asked the same question, and she turned away remarking casually, 'Well, of course, it's the Flood'."

4.2 Floods in China

The 1887 Yellow River flood

In places, the Yellow River runs between dykes that are elevated above the surrounding countryside, and thus it is prone to flooding, The flood that occurred in 1887 killed at least 900,000 people. Estimates of the death toll range as high as 2,000,000.

The 1931 Yangtze-Huai-River floods

These were a series of floods that hit the cities of Wuhan and Nanjing, and ultimately culminated in the breach of a dyke along Lake Gaoyou. The estimates of fatalities differ very widely. Probably about 2 million people died as a result of the floods, most of the deaths coming not from drowning but from starvation and flood-related epidemics.

The 1938 Yellow River Flood

This flood, which has been called "the largest act of environmental warfare in history" was deliberately caused by the Chinese Nationalists to halt the advance of the Japanese army that was invading China. The flood caused roughly 800,000 deaths, and approximately 10,000,000 refugees.

4.3 Floods in India and Bangladesh

India

Wikipedia gives the following list of floods in India in the 21st century;

- **Heavy rains across the state of Maharashtra, including large areas of the metropolis Mumbai... on 26 July 2005 killed at least 1,094 people. The day is still remembered as the day Mumbai came to a standstill, as the city faced worst ever rain. Mumbai International Airport remained closed for 30 hours, Mumbai-Pune Expressway was closed for 24 hours with public property loss was estimated at US$77 million.**

- **June 2013 North Indian floods: Heavy rain due to a burst of a cloud caused severe floods and landslides on the North Indian states, mainly Uttarakhand and nearby states. More than 5,700 people were presumed dead.**

- **June 2015 Gujarat flood: Heavy rain in June 2015 resulted in widespread flood in Saurashtra region of Gujarat resulting in more than 70 deaths. The wild life of Gir Forest National Park and adjoining area was also affected.**

- **July 2015 Gujarat flood:Heavy rain in July 2015 resulted in widespread flood in north Gujarat resulting in more than 70 deaths.**

- **2015 South Indian floods:Heavy rain in Nov-Dec 2015 resulted in flooding of Adyar, Cooum rivers in Chennai, Tamil Nadu resulting in financial loss and human lives.**

- **2016 Assam floods: Heavy rains in July-August resulted in floods affecting 1.8 million people and flooding the Kaziranga National Park killing around 200 wild animals.**

- **2017 Gujarat flood: Following heavy rain in July 2017, Gujarat state of India was affected by the severe flood resulting in more than 200 deaths.**
- **August 2018 Kerala Flood: Following high rain in late August 2018 and heavy Monsoon rainfall from August 8, 2018, severe flooding affected the Indian state of Kerala resulting over 445 deaths.**
- **August 2019 Indian floods including 2019 Kerala floods: Following high rain in late July and early August 2019, series of floods that affected over nine states in India. The states of Kerala, Madhya Pradesh, Karnataka, Maharashtra and Gujarat were the most severely affected.**
- **Brahmaputra floods**
- **2020 Assam floods**

Climate change is thought to be a major cause of recent severe flooding in India.

Figure 4.2: **People seeking refuge from flood in Jawa Tengah, Java. ca. 1865-1876.**

Bangladesh

Bangladesh is a low-lying country, situated on the Ganges river delta, and is thus very prone to flooding. Wikipedia describes the situation as follows:

"Each year in Bangladesh about 26,000 square kilometers (10,000 sq mi) (around 18% of the country) is flooded, killing over 5,000 people and destroying more than seven million homes. During severe floods the affected area may exceed 75% of the country, as was seen in 1998. This volume is 95% of the total annual inflow. By comparison, only about 187 trillion l (1.87×1011 m3; 6.6×1012 cu ft) of streamflow is generated by rainfall inside the country during the same period. The floods have caused devastation in Bangladesh throughout history, especially in 1951, 1987, 1988 and 1998. The 2007 South Asian floods also affected a large portion of Bangladesh."

Figure 4.3: **Flooding after 1991 Bangladesh cyclone, which killed around 140,000 people.**

4.4 Floods in East Africa

Six million people affected in 2020

The BBC reported that 6 million people were affected by the 2020 floods in East Africa. Of these, 1.5 million were forced to flee from their homes.

Data collected by the United Nations indicates that flooding in East Africa has increased more than five fold in four years, This finding makes it probable that climate change is involved.

4.5 Tsunamis

The 2004 Indian Ocean earthquake and tsunami

On the 26th of December, 2004, an enormous earthquake occurred under the waters of the Indian Ocean. It was one of the largest earthquakes ever recorded, and it lasted longer than any other recorded earthquake. It caused the earth to vibrate so much that it triggered other earthquakes as far away as Alaska.

The tsunami produced by the 2004 Indian Ocean earthquake killed an estimated 227,898 people in 14 countries.

The 2011 Fukushima tsunami and nuclear disaster

On the 11th of March, 2011, a massive earthquake occurred under the sea off the coast of Japan, east of the Oshika Peninsula of Tohoku. It was the largest earthquake ever recorded near to Japan, and the fourth largest recorded in the world, since record-keeping began in 1900.

As it reached the shore, the tsunami wave caused by the earthquake was 40 meters high. Besides causing loss of life through drowning and the loss of homes, property and infrastructure, the tsunami initiated a nuclear disaster at the Fukushima Daiichi Nuclear Power Plant. The disaster, which continues to release radioactive water into the Pacific ocean even today, ranks with the Chernobyl as one of the two worst nuclear disasters in history.

The total damage inflicted by the tsunami wave is estimated as $235 billion ($235,000,000,000), making it the costliest natural disaster in history.

4.6 Flooding from hurricanes

Katrina, 2005

Hurricane Katrina was a category 5 Atlantic hurricane that hit Florida before turning westward and flooding New Orleans. Damage produced by Katrina amounted to $125

Figure 4.4: **View of flooded New Orleans in the aftermath of Hurricane Katrina.**

billion. This made it, at the time the costliest Atlantic Hurricane, but it was later tied by Hurricane Harvey.

The city of New Orleans lies below sea level, but it was protected by levees built by the US Army Corps of Engineers. When Katrina hit, the levees protecting New Orleans failed, and 80% of the city was flooded for weeks. Residents who had not been evacuated were left in desperate need of food, clean water, and other services. The Corps of Engineers was blamed for faulty construction of the levees, but not required to pay for damage. An emergency was declared, and much help for New Orleans came from other parts of the country.

Sandy, 2012

Hurricane Sandy was an Atlantic hurricane that was remarkable, not for its intensity, but for its enormous size. Sandy's storm-force winds stretched 1,150 miles, or 1.885 kilometers, making it the largest hurricane on record. Sandy caused $70 billion in damage, and killed 233 people in eight countries, not only in the Caribbean, but also in the United States and Canada.

In New York City, water from Sandy's storm surge poured into subways, short-circuiting New York's electrical power systems and giving the city a long-lasting blackout.

Harvey, 2017

Harvey made landfall in Texas as a category 4 hurricane, causing catastrophic flooding, 100 deaths, and $125 billion in damage, making it the costliest hurricane in Texas history, and tied for first place nationally with Katrina. Many areas in Texas received a meter of rainfall in 24 hours. Toxic chemicals from oil refineries flowed out over the city of Huston.

Although the mass media almost have entirely neglected the link between climate change and recent disastrous hurricanes, floods droughts and wildfires, many individuals and organizations emphasized the cause and effect relationship. For example, UK airline billionaire Sir Richard Branson, whose Caribbean summer residence was destroyed by Hurricane Irma said:

"Look, you can never be 100 percent sure about links, But scientists have said the storms are going to get more and more and more intense and more and more often. We've had four storms within a month, all far greater than that have ever, ever, ever happened in history, Sadly, I think this is the start of things to come. Climate change is real. Ninety-nine percent of scientists know it's real. The whole world knows it's real except for maybe one person in the White House."

May Boeve, executive director of the NGO 350.org, said "With a few exceptions, the major TV networks completely failed to cover the scientifically proven ways that climate change is intensifying extreme weather events like hurricanes Harvey and Irma. That's not just disappointing, it's dangerous. We won't be able to turn this crisis around if our media is asleep at the wheel."

Commenting on the destruction of Puerto Rico by Hurricane Maria, historian Juan Cole wrote: "When you vote for denialist politicians, you are selecting people who make policy. The policy they make will be clueless and will actively endanger the public. Climate change is real. We are causing it by our emissions. If you don't believe that, you are not a responsible steward of our infrastructure and of our lives."

When interviewed by Amy Goodman of *Democracy Now*, musician Stevie Wonder said: "... we should begin to love and value our planet, and anyone who believes that there is no such thing as global warming must be blind or unintelligent."

Another well-known musician, Byoncé, added: "The effects of climate change are playing out around the world every day. Just this past week, we've seen devastation from the monsoon in India...and multiple catastrophic hurricanes. Irma alone has left a trail of death and destruction from the Caribbean to Florida to Southern United States. We have to be prepared for what comes next..."

In her September 2017 publication *Season of Smoke*[1], prizewinning author Naomi Klein wrote:

"We hear about the record-setting amounts of water that Hurricane Harvey dumped on Houston and other Gulf cities and towns, mixing with petrochemicals to pollute and poison on an unfathomable scale. We hear too about the epic floods that have displaced hundreds of thousands of people from Bangladesh to Nigeria (though we don't hear enough). And we are witnessing, yet again, the fearsome force of water and wind as Hurricane Irma, one of the most powerful storms ever recorded, leaves devastation behind in the Caribbean, with Florida now in its sights.

"Yet for large parts of North America, Europe, and Africa, this summer has not been about water at all. In fact it has been about its absence; it's been about land so dry and heat so oppressive that forested mountains exploded into smoke like volcanoes. It's been about fires fierce enough to jump the Columbia River; fast enough to light up the outskirts of Los Angeles like an invading army; and pervasive enough to threaten natural treasures, like the tallest and most ancient sequoia trees and Glacier National Park.

"For millions of people from California to Greenland, Oregon to Portugal, British Columbia to Montana, Siberia to South Africa, the summer of 2017 has been the summer of fire. And more than anything else, it's been the summer of ubiquitous, inescapable smoke.

"For years, climate scientists have warned us that a warming world is an extreme world, in which humanity is buffeted by both brutalizing excesses and stifling absences of the core elements that have kept fragile life in equilibrium for millennia. At the end of the summer of 2017, with major cities submerged in water and others licked by flames, we are currently living through Exhibit A of this extreme world, one in which natural extremes come head-to-head with social, racial, and economic ones."

It seems likely that the climate-linked disasters of 2019 and 2020 will be even more severe than those that we have witnessed during 2017 and 2018. But will such disasters

[1] https://theintercept.com/2017/09/09/in-a-summer-of-wildfires-and-hurricanes-my-son-asks-why-is-everything-going-wrong/

be enough to wake us up?

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Chapter 5

WATER AND THE THREAT OF FAMINE

5.1 Lester Brown's lecture in Copenhagen

After a lecture at the University of Copenhagen in the 1980's, Lester R. Brown of the Earth Policy Institute was asked which resource would be the first to become critically scarce. Everyone in the audience expected him to say "oil", but instead he said "fresh water". He went on to explain that falling water tables in China would soon make China unable to feed its population. This would not cause famine in China itself because of the strength of the Chinese economy, which would allow the Chinese to purchase grain on the world market. However, shortages of fresh water in China would indeed cause famine, for example in Africa, because Chinese demand for grain would raise prices on the world market beyond the ability of poor countries to pay.

5.2 Predictions of drought in the Stern Review

According to a report presented to the Oxford Institute of Economic Policy by Sir Nicholas Stern on 31 January, 2006, areas likely to lose up to 30% of their rainfall by the 2050's because of climate change include much of the United States, Brazil, the Mediterranean region, Eastern Russia and Belarus, the Middle East, Southern Africa and Southern Australia. Meanwhile rainfall is predicted to increase up to 30% in Central Africa, Pakistan, India, Bangladesh, Siberia, and much of China.

Stern and his team point out that "We can... expect to see changes in the Indian monsoon, which could have a huge impact on the lives of hundreds of millions of people in India, Pakistan and Bangladesh. Most climate models suggest that the monsoon will change, although there is still uncertainty about exactly how. Nevertheless, small changes in the monsoon could have a huge impact. Today, a fluctuation of just 10% in either direction from average monsoon rainfall is known to cause either severe flooding or drought. A weak summer monsoon, for example, can lead to poor harvests and food shortages among the rural population - two-thirds of India's almost 1.1 billion people. Heavier-than-usual monsoon downpours can also have devastating consequences..."

In some regions, melting of glaciers can be serious from the standpoint of dry-season water supplies. For example, melts from glaciers in the Hindu Kush and the Himalayas now supply much of Asia, including China and India, with a dry-season water supply. Complete melting of these glacial systems would cause an exaggerated runoff for a few decades, after which there would be a drying out of some of the most densely populated regions of the world.

5.3 Ocean current changes and failure of monsoons

It is expected that climate change will affect ocean currents, and hence also affect monsoon rainfall. We are already experiencing a diversion of the Gulf Stream due to southward currents of cold water from melting ice in the Arctic. This has caused what is known as the *North Atlantic Anomaly.* While most regions of the world are experiencing rising temperatures, the North Atlantic and several northern European countries are exceptions to this rule, and have cooled. Complete failure of the Gulf Stream would lead to much colder temperatures in Europe.

Changes in ocean currents have already lead to the failure of the West African Monsoon, and this has already produced severe food insecurity in West Africa.

In the future, climate-changed ocean currents may lead to failures of monsoons in South-east Asia, and thus damage the food supply of almost two billion people.

5.4 Falling water tables around the world

Under many desert areas of the world are deeply buried water tables formed during glacial periods when the climate of these regions was wetter. These regions include the Middle East and large parts of Africa. Water can be withdrawn from such ancient reservoirs by deep wells and pumping, but only for a limited amount of time.

In oil-rich Saudi Arabia, petroenergy is used to drill wells for ancient water and to bring it to the surface. Much of this water is used to irrigate wheat fields, and this is done to such an extent that Saudi Arabia exports wheat. The country is, in effect, exporting its ancient heritage of water, a policy that it may, in time, regret. A similarly short-sighted project is Muammar Qaddafi's enormous pipeline, which will bring water from ancient sub-desert reservoirs to coastal cities.

In the United States, the great Ogallala aquifer is being overdrawn. This aquifer is an enormous stratum of water-saturated sand and gravel under-lying parts of northern Texas, Oklahoma, New Mexico, Kansas, Colorado, Nebraska, Wyoming and South Dakota. The average thickness of the aquifer is about 70 meters. The rate of water withdrawal from the aquifer exceeds the rate of recharge by a factor of eight.

Thus we can see that in many regions, the earth's present population is living on its inheritance of water, rather than its income. This fact, coupled with rapidly increasing populations and climate change, may contribute to a very serious food crisis partway through the 21st century.

5.5 The Green Revolution

In 1944 the Norwegian-American plant geneticist Norman Borlaug was sent to Mexico by the Rockefeller Foundation to try to produce new wheat varieties that might increase Mexico's agricultural output. Borlaug's dedicated work on this project was spectacularly successful. He remained with the project for 16 years, and his group made 6,000 individual crossings of wheat varieties to produce high-yield disease-resistant strains.

In 1963, Borlaug visited India, bringing with him 100 kg. of seeds from each of his most promising wheat strains. After testing these strains in Asia, he imported 450 tons of the Lerma Rogo and Sonora 64 varieties - 250 tons for Pakistan and 200 for India. By 1968, the success of these varieties was so great that school buildings had to be commandeered to store the output. Borlaug's work began to be called a "Green Revolution". In India, the research on high-yield crops was continued and expanded by Prof. M.S. Swaminathan and his coworkers. The work of Green Revolution scientists, such Norman Borlaug and M.S. Swaminathan, has been credited with saving the lives of as many as a billion people.

Despite these successes, Borlaug believes that the problem of population growth is still a serious one. "Africa and the former Soviet republics", Borlaug states, "and the Cerrado[1], are the last frontiers. After they are in use, the world will have no additional sizable blocks of arable land left to put into production, unless you are willing to level whole forests, which you should not do. So, future food-production increases will have to come from higher yields. And though I have no doubt that yields will keep going up, whether they can go up enough to feed the population monster is another matter. Unless progress with agricultural yields remains very strong, the next century will experience human misery that, on a sheer numerical scale, will exceed the worst of everything that has come before."

A very serious problem with Green Revolution plant varieties is that they require heavy inputs of pesticides, fertilizers and irrigation. Because of this, the use of high-yield varieties contributes to social inequality, since only rich farmers can afford the necessary inputs. Monocultures, such as the Green Revolution varieties may also prove to be vulnerable to future epidemics of plant diseases, such as the epidemic that caused the Irish Potato Famine in 1845. Even more importantly, pesticides, fertilizers and irrigation all depend on the use of fossil fuels. One must therefore ask whether high agricultural yields can be maintained in the future, when fossil fuels are expected to become prohibitively scarce and expensive.

[1] The Cerrado is a large savanna region of Brazil.

Figure 5.1: **Norman Borlaug's work on developing high-yield disease-resistant plant varieties won him a Nobel Peace Prize in 1970.**

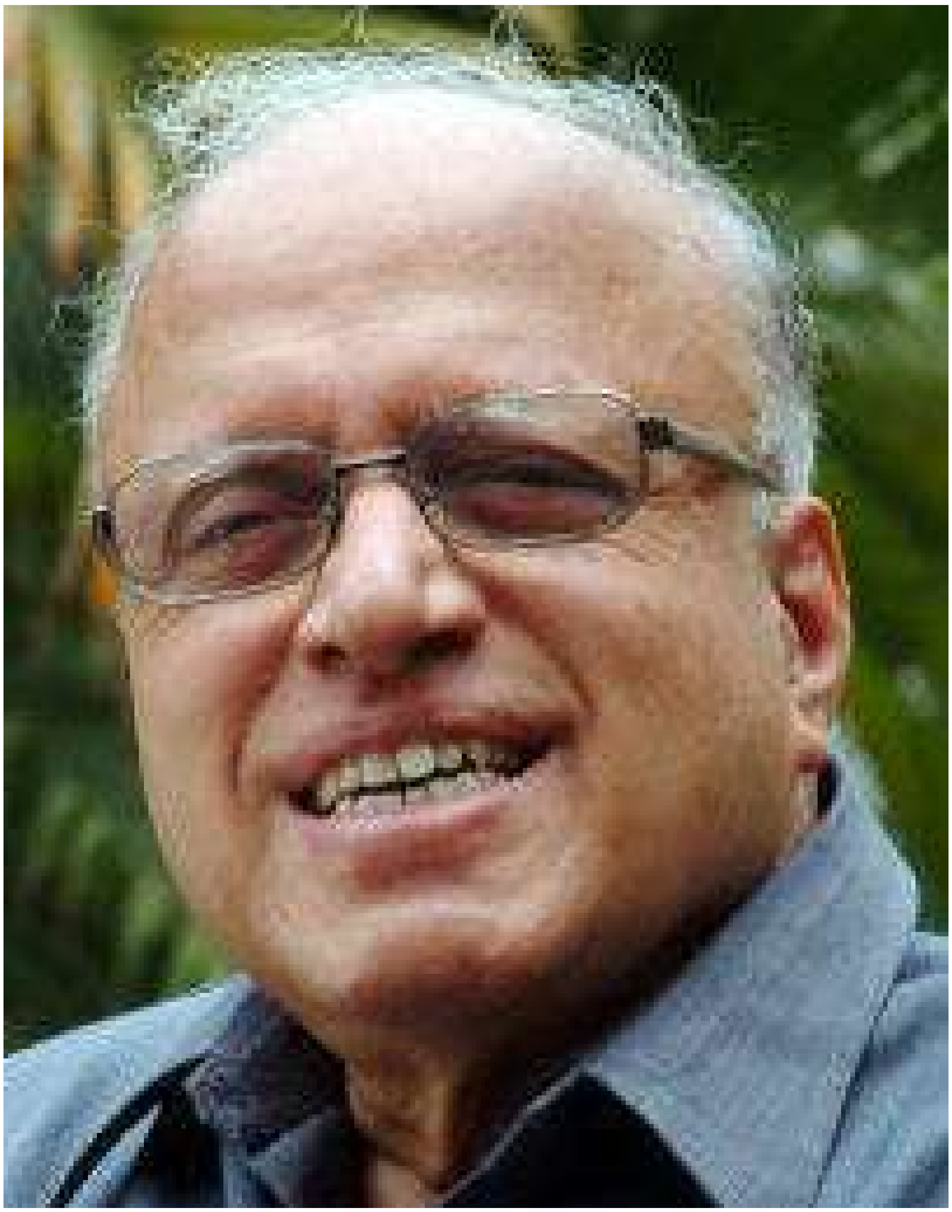

Figure 5.2: **Professor M.S. Swaminathan, father of the Green Revolution in India.**

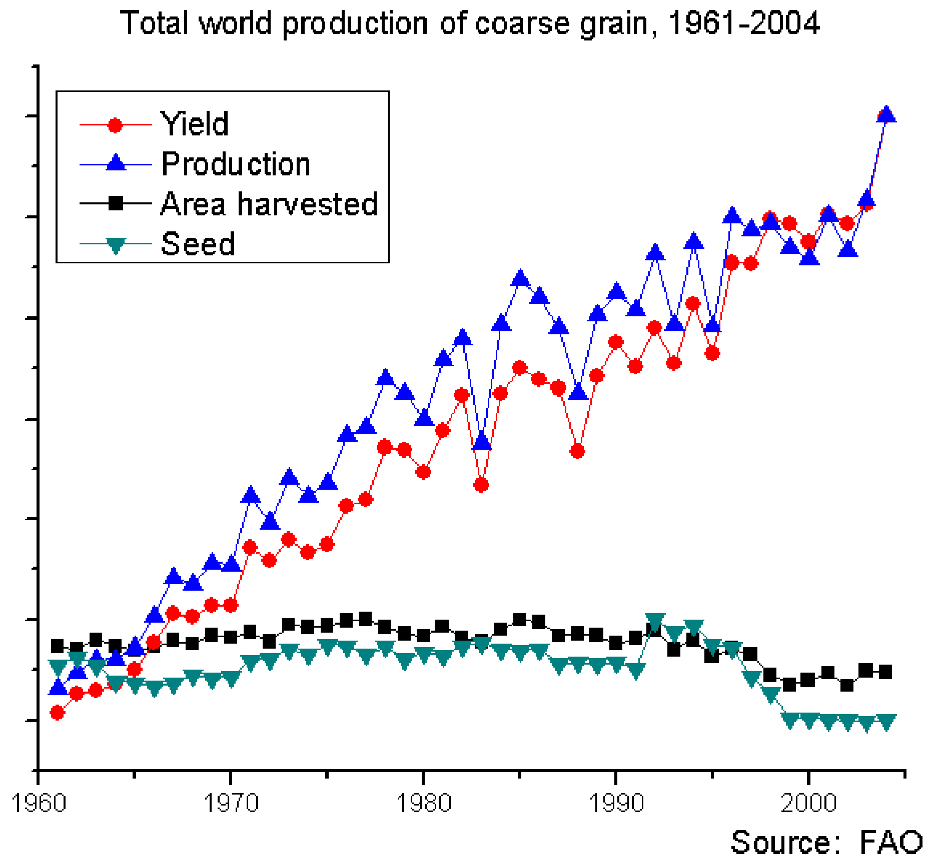

Figure 5.3: **This graph shows the total world production of coarse grain between 1960 and 2004. Because of high-yield varieties, the yield of grain increased greatly. Notice, however, that the land under cultivation remained almost constant. High-yield agriculture depends on large inputs of fossil fuel energy and irrigation, and may be difficult to maintain in the future.**

5.6 Energy inputs of agriculture

Modern agriculture has become highly dependent on fossil fuels, especially on petroleum and natural gas. This is especially true of production of the high-yield grain varieties introduced in the Green Revolution, since these require especially large inputs of fertilizers, pesticides and irrigation. Today, fertilizers are produced using oil and natural gas, while pesticides are synthesized from petroleum feedstocks, and irrigation is driven by fossil fuel energy. Thus agriculture in the developed countries has become a process where inputs of fossil fuel energy are converted into food calories. If one focuses only on the farming operations, the fossil fuel energy inputs are distributed as follows:

1. Manufacture of inorganic fertilizer, 31%
2. Operation of field machinery, 19%
3. Transportation, 16%
4. Irrigation, 13%
5. Raising livestock (not including livestock feed), 8%
6. Crop drying, 5%
7. Pesticide production, 5%
8. Miscellaneous, 8%

The ratio of the fossil fuel energy inputs to the food calorie outputs depends on how many energy-using elements of food production are included in the accounting. David Pimentel and Mario Giampietro of Cornell University estimated in 1994 that U.S. agriculture required 0.7 kcal of fossil fuel energy inputs to produce 1.0 kcal of food energy. However, this figure was based on U.N. statistics that did not include fertilizer feedstocks, pesticide feedstocks, energy and machinery for drying crops, or electricity, construction and maintenance of farm buildings. A more accurate calculation, including these inputs, gives an input/output ratio of approximately 1.0. Finally, if the energy expended on transportation, packaging and retailing of food is included, Pimentel and Giampietro found that the input/output ratio for the U.S. food system was approximately 10, and this figure did not include energy used for cooking.

5.7 Sustainable future populations

In an important and detailed study entitled *Will Limited Land, Water, and Energy Control Human Population Numbers in the Future?*, David Pimentel et al. [2] discuss the problem

[2] D. Pimentel et al., Human Ecology DOI 10.1007/s10745-010-9346-y, (2010)

of agriculture and global population in the post fossil fuel era. Here are some quotations from the article:

“Nearly 60% of the world’s human population is malnourished and the numbers are growing. Shortages of basic foods related to decreases in per capita cropland, water, and fossil energy resources contribute to spreading malnutrition and other diseases. The suggestion is that in the future only a smaller number of people will have access to adequate nourishment. In about 100 years, when it is reported that the planet will run out of fossil energy, we suggest that a world population of about two billion might be sustainable if it relies on renewable energy technologies and also reduces per capita use of the earth’s natural resources.

“Developed and developing nations need to provide a good quality life for their people while coping with rapid population growth, but ’Population is the issue no one wants to touch’ (Meadows 2000). The current world population is about 6.8 billion. Based on the present growth rate of 1.2% per year, the population is projected to double in approximately 58 years (Chiras 2006; PRB 2008). Because population growth cannot continue indefinitely, society can either voluntarily control its numbers or let natural forces such as disease, malnutrition, and other disasters limit human numbers (Bartlett 1997-98; Pimentel et al. 1999). Increasing human numbers especially in urban areas, and increasing pollution of food, water, air, and soil by pathogenic disease organisms and chemicals, are causing a rapid increase in the prevalence of disease and human mortality (Murray and Lopez 1996; Pimentel et al. 2007). Currently, more than 3.7 billion humans are malnourished worldwide - the largest number ever (WHO 2005a, b).

“The planet’s numerous environmental problems highlight the urgent need to evaluate available land, water, and energy resources and how they relate to the requirements of a rapidly growing human population (Pimentel and Pimentel 2008). In this article we assess the carrying capacity of the Earth’s natural resources, and suggest that humans should voluntarily limit their population growth, rather than letting natural forces control their numbers (Ferguson 1998; Pimentel et al. 1999). In addition, we suggest appropriate policies and technologies that would improve standards of living and quality of life worldwide...

“In 1960, when the world population numbered about 3 billion, approximately 0.5 ha of cropland was available per capita worldwide. This half a hectare is needed to provide a diverse, healthy, nutritious diet of plant and animal products...”

Pimentel et al. state that worldwide, the average cropland per capita has now fallen to 0.22 hectares. This number will continue to fall because global population is increasing at the rate of almost one billion people per decade, while the global area available for cropland is not increasing. On the contrary, it is decreasing because of desertification, erosion, salination and urban sprawl. Pimentel et al.state that cropland is being degraded and lost at a rate of more than 20 million hectares per year.

The current cropland per capita in the United States is 0.56 hectares, and thus still quite large, but in China, the figure is dangerously low: only 0.1 hectares. China will soon be unable to feed its population and will have to buy grain on the world market. As Lester Brown pointed out in his Copenhagen lecture, China will be able to import grain because of its strong economy, but this will raise food prices and will cause widespread famine in other parts of the world.

Added to the agricultural and environmental problems, are problems of finance and distribution. Famines can occur even when grain is available somewhere in the world, because those who are threatened with starvation may not be able to pay for the grain, or for its transportation. The economic laws of supply and demand are not able to solve this type of problem. One says that there is no "demand" for the food (meaning demand in the economic sense), even though people are in fact starving.

What is the optimum population of the world? It is certainly not the maximum number that can be squeezed onto the globe by eradicating every species of plant and animal that cannot be eaten. The optimum global population is one that can be supported in comfort, equality and dignity - and with respect for the environment.

In 1848 (when there were just over one billion people in the world), John Stuart Mill described the optimal global population in the following words:

"The density of population necessary to enable mankind to obtain, in the greatest degree, all the advantages of cooperation and social intercourse, has, in the most populous countries, been attained. A population may be too crowded, although all be amply supplied with food and raiment."

"... Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature; with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or natural pasture plowed up, all quadrupeds or birds which are not domesticated for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out, and scarcely a place left where a wild shrub or flower could grow without being eradicated as a weed in the name of improved agriculture. If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increase of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger, but not better or happier population, I sincerely hope, for the sake of posterity, that they will be content to be stationary, long before necessity compels them to it."[3]

Dennis Meadows, one of the authors of *Limits to Growth*, stated recently that the optimum human population in the distant future may be about 2 billion people.

But what about the near future? Will the global population of humans crash catastrophically after having exceeded the carrying capacity of the environment? There is certainly a danger that this will happen - a danger that the 21st century will bring very large scale famines to vulnerable parts of the world, because modern energy-intensive agriculture will be dealt a severe blow by prohibitively high petroleum prices. At present, there are only a few major food-exporting countries, notably the United States, Canada, Australia and Argentina. There is a danger that within a few decades, the United States will no longer be able to export food because of falling production and because of the demands of a growing population. We should be aware of these serious future problems if we are to have a chance of avoiding them.

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[3]John Stuart Mill, *Principles of Political Economy, With Some of Their Applications to Social Philosophy*, (1848).

5.8 The demographic transition

The developed industrial nations of the modern world have gone through a process known as the "demographic transition" - a shift from an equilibrium where population growth is held in check by the grim Malthusian forces of disease, starvation and war, to one where it is held in check by birth control and late marriage.

The transition begins with a fall in the death rate, caused by various factors, among which the most important is the application of scientific knowledge to the prevention of disease. Malthus gives the following list of some of the causes of high death rates: "...unwholesome occupations, severe labour and exposure to the seasons, extreme poverty, bad nursing of children, great towns, excesses of all kinds, the whole train of common diseases and epidemics, wars, plague and famine." The demographic transition begins when some of the causes of high death rates are removed.

Cultural patterns require some time to adjust to the lowered death rate, and so the birth rate continues to be high. Families continue to have six or seven children, just as they did when most of the children died before having children of their own. Therefore, at the start of the demographic transition, the population increases sharply. After a certain amount of time, however, cultural patterns usually adjust to the lowered death rate, and a new equilibrium is established, where both the birth rate and the death rate are low.

In Europe, this period of adjustment required about two hundred years. In 1750, the death rate began to fall sharply: By 1800, it had been cut in half, from 35 deaths per thousand people in 1750 to 18 in 1800; and it continued to fall. Meanwhile, the birth rate did not fall, but even increased to 40 births per thousand per year in 1800. Thus the number of children born every year was more than twice the number needed to compensate for the deaths!

By 1800, the population was increasing by more than two percent every year. In 1750, the population of Europe was 150 million; by 1800, it was roughly 220 million; by 1950 it had exceeded 540 million, and in 1970 it was 646 million.

Meanwhile the achievements of medical science and the reduction of the effects of famine and warfare had been affecting the rest of the world: In 1750, the non-European population of the world was only 585 million. By 1850 it had reached 877 million. During the century between 1850 and 1950, the population of Asia, Africa and Latin America more than doubled, reaching 1.8 billion in 1950. In the twenty years between 1950 and 1970, the population of Asia, Africa and Latin America increased still more sharply, and in 1970, this segment of the world's population reached 2.6 billion, bringing the world total to 3.6 billion. The fastest increase was in Latin America, where population almost doubled during the twenty years between 1950 and 1970.

The latest figures show that population has stabilized or in some cases is even decreasing in Europe, Russia, Canada, Japan, Cuba and New Zealand. In Argentina, the United States, China, Myanmar, Thailand and Australia, the rates of population increase are moderate - 0.6%-1.0%; but even this moderate rate of increase will have a heavy ecological impact, particularly in the United States, with its high rates of consumption.

The population of the remainder of the world is increasing at breakneck speed - 2%-4%

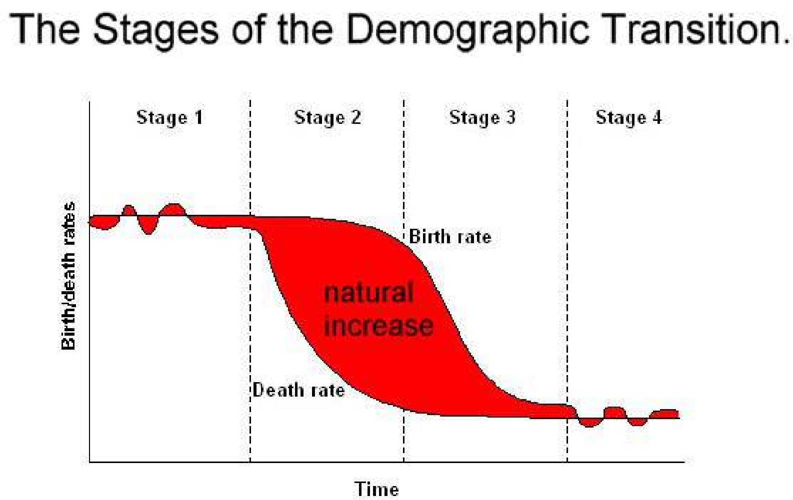

Figure 5.4: **The demographic transition.**

per year - and it cannot continue to expand at this rate for very much longer without producing widespread famines, since modern intensive agriculture cannot be sustained beyond the end of the fossil fuel era. The threat of catastrophic future famines makes it vital that all countries that have not completed the demographic transition should do so as rapidly as possible.

5.9 Urbanization

The global rate of population growth has slowed from 2.0 percent per year in 1972 to 1.7 percent per year in 1987; and one can hope that it will continue to fall. However, it is still very high in most developing countries. For example, in Kenya, the population growth rate is 4.0 percent per year, which means that the population of Kenya will double in seventeen years.

During the 60 years between 1920 and 1980 the urban population of the developing countries increased by a factor of 10, from 100 million to almost a billion. In 1950, the population of Sao Paulo in Brazil was 2.7 million. By 1980, it had grown to 12.6 million; and it is expected to reach 24.0 million by the year 2000. Mexico City too has grown explosively to an unmanageable size. In 1950, the population of Mexico City was 3.05 million; in 1982 it was 16.0 million; and the population in 2000 was 17.8 million.

A similar explosive growth of cities can be seen in Africa and in Asia. In 1968, Lusaka, the capital of Zambia, and Lagos, the capital of Nigeria, were both growing at the rate of 14 percent per year, doubling in size every 5 years. In 1950, Nairobi, the capital of Kenya, had a population of 0.14 million. In a 1999 census, it was estimated to be between 3 and 4 million, having increased by a factor of 25.

Figure 5.5: **Because of the threat of widespread famine, it is vital that all countries should complete the demographic transition as quickly as possible.**

Figure 5.6: **Sir Partha Dasgupta of Cambridge University has pointed out that all the changes needed for population stabilization are desirable in themselves. These include education for women, higher status for women, state provision of old-age help for the poor, universal health care, and making safe drinking water available near to dwellings.**

In 1972, the population of Calcutta was 7.5 million. By the turn of the century in 2000, it had almost doubled in size. This rapid growth produced an increase in the poverty and pollution from which Calcutta already suffered in the 1970's. The Hooghly estuary near Calcutta is choked with untreated industrial waste and sewage, and a large percentage of Calcutta's citizens suffer from respiratory diseases related to air pollution.

Governments in the third world, struggling to provide clean water, sanitation, roads, schools, medical help and jobs for all their citizens, are defeated by rapidly growing urban populations. Often the makeshift shantytowns inhabited by new arrivals have no piped water; or when water systems exist, the pressures may be so low that sewage seeps into the system.

Many homeless children, left to fend for themselves, sleep and forage in the streets of third world cities. These conditions have tended to become worse with time rather than better. Whatever gains governments can make are immediately canceled by growing populations.

5.10 Achieving economic equality

Today's world is characterized by intolerable economic inequalities, both between nations and within nations. A group of countries including (among others) Japan, Germany, France, the United Kingdom and the United States, has only 13% of the world's population, but receives 45% of the global PPP[4] income. By contrast, a second group, including 2.1 Billion people (45% of the world's population) receives only 9% of the global PPP income. Another indicator of inequality is the fact that the 50 million richest people in the world receive as much as the 2,700 million poorest.

18 million of our fellow humans die each year from poverty-related causes. Each year, 11 million children die before reaching their fifth birthday. 1.1 billion people live on less than $1 per day; 2.7 billion live on less than $2.

At the United Nations Conference on Population and Development, held in Cairo in September, 1994, a theme which emerged very clearly was that one of the most important keys to controlling the global population explosion is giving women better education and equal rights. These goals are desirable for their own sake, and for the sake of the uniquely life-oriented point of view which women can give us; but in addition, education and improved status for women have shown themselves to be closely connected with lowered birth rates. When women lack education and independent careers outside the home, they can be forced into the role of baby-producing machines by men who do not share in the drudgery of cooking, washing and cleaning; but when women have educational, legal, economic, social and political equality with men, experience has shown that they choose to limit their families to a moderate size.

As glaciers melt in the Himalayas, depriving India and China of summer water supplies; as sea levels rise, drowning the fertile rice fields of Viet Nam and Bangladesh; as drought

[4] Purchasing Power Parity

Figure 5.7: **Education of women and higher status for women are vitally important measures, not only for their own sake, but also because these social reforms have proved to be the key to lower birth rates.**

threatens the productivity of grain-producing regions of North America; and as the end of the fossil fuel era impacts modern high-yield agriculture, there is a threat of wide-spread famine. There is a danger that the billions of people who are undernourished today will not survive an even more food-scarce future.

People threatened with famine will become refugees, desperately seeking entry into countries where food shortages are less acute. Wars, such as those currently waged in the Middle East, will add to the problem.

What can we do to avoid this crisis, or at least to reduce its severity? We must urgently address the problem of climate change; and we must shift money from military expenditure to the support of birth control programs and agricultural research. We must also replace the institution of war by a system of effective global governance and enforcible international laws.

5.11 Achieving a steady-state economic system

Endless economic growth on a finite planet is a logical impossibility. Just as population growth is limited by ecological constraints, so too is the growth of resource-using and pollution-producing industrial production. Culture, of course, can and should continue to grow,

A number of economists have studied this problem, and in particular, outstanding contributions have been made by Frederick Soddy, Nickolas Georgiescu-Roegan and Herman Daly. These authors have taken into account the role which entropy plays in economics.

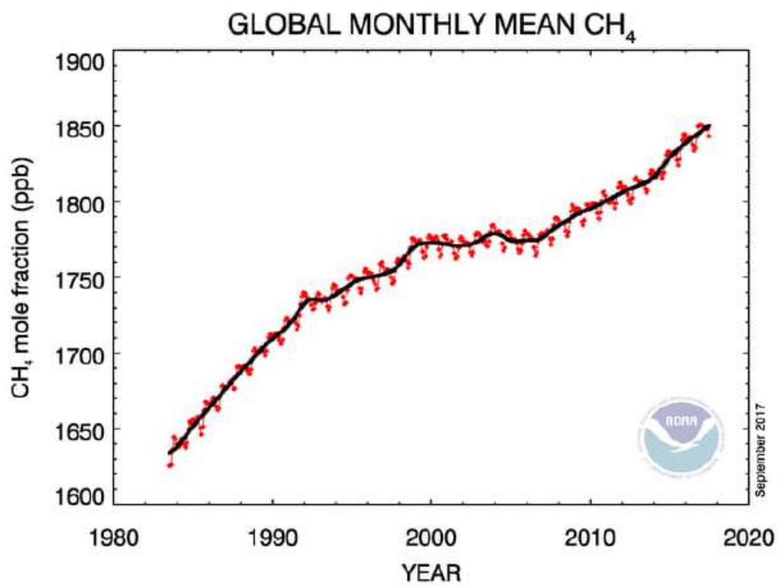

Figure 5.8: **Methane emissions are steadily increasing. A new report has shown ruminants are largely responsible for increases in rates of emission.**

5.12 Harmful effects of industrialized farming

Pharming

A major global public health crisis may soon be produced by the wholesale use of antibiotics in the food of healthy farm animals. The resistance factors produced by shovelling antibiotics into animal food produces resistance factors (plasmids) which can easily be transferred to human pathogens. A related problem is the excessive use of pesticides and artificial fossil-fuel-derived fertilizers in agriculture. Pharming is not a joke. It is a serious threat.[5]

Meat and methane

Methane is an extremely powerful greenhouse gas. and it is emitted in large quantities by ruminants, such as cattle produced for beef. A new report[6] finds that cattle are not the biggest contributor to the annual methane budget in the atmosphere, but they may be the biggest contributor to increases in methane emissions over recent years.

One must also remember that by eating less meat, and in particular less beef, we can shorten the food chain and thus help famine-threatened populations.

Pesticides, artificial fertilizers and topsoil

A closely analogous danger results from the overuse of pesticides and petroleum-derived fertilizers in agriculture. A very serious problem with Green Revolution plant varieties is that they require heavy inputs of pesticides, fertilizers and irrigation. Because of this, the use of high-yield varieties contributes to social inequality, since only rich farmers can afford the necessary inputs. Monocultures, such as the Green Revolution varieties may also prove to be vulnerable to future plant diseases, such as the epidemic that caused the Irish Potato Famine in 1845. Even more importantly, pesticides, fertilizers and irrigation all depend on the use of fossil fuels. One must ask, therefore, whether high-yield agriculture can be maintained in the post-fossil-fuel era.

Topsoil is degraded by excessive use of pesticides and artificial fertilizers. Natural topsoil is rich in organic material, which contains sequestered carbon that would otherwise be present in our atmosphere in the form of greenhouse gases. In addition, natural topsoil contains an extraordinarily rich diversity of bacteria and worms that act to convert agricultural wastes from one year's harvest into nutrients for the growth of next year's crop. Pesticides kill these vital organisms, and make the use of artificial fertilizers necessary.

Finally, many small individual farmers, whose methods are sustainable, are being eliminated by secret land-grabs or put out of business because they cannot compete with unsustainable high-yield agriculture. Traditional agriculture contains a wealth of knowledge and biodiversity, which it would be wise for the world to preserve.

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[5]http://ecowatch.com/2014/03/06/misuse-antibiotics-fatal-superbug-crisis/
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[6]J. Wolf et al., *Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock*, Carbon Balance and Management 2017, 12:16

5.13 Several billion people might suffer

There is a danger that population growth, climate change and the end of the fossil fuel era could combine to produce an extremely large-scale global famine by the middle of the present century. Such a famine might involve several billion people, rather than millions.

5.14 Child mortality rates

Here are some quatitions from an article entitled *Child mortality rates drop but 15,000 children under 5 still die each day*, published in Agriculture at a Crossroads on September 18, 2018:[7]

Although the global number of child deaths remains high, the world has made tremendous progress in reducing child mortality over the past few decades. The total number of under-five deaths dropped to 5.3 million in 2018, down from 12.5 million in 1990. This is the main message of a report published today by UN organizations led by UNICEF and the World Health Organization (WHO). According to the "Levels and trends in child mortality: Report 2019", more women and their children are surviving today than ever before. Since 2000, child deaths have reduced by nearly half and maternal deaths by over one-third, mostly due to improved access to affordable, quality health services. However, in 2018 alone, 15,000 children died per day before reaching their fifth birthday. "It is especially unacceptable that these children and young adolescents died largely of preventable or treatable causes like infectious diseases and injuries when we have the means to prevent these deaths," the authors write in the introduction to the report. The global under-five mortality rate fell to 39 deaths per 1,000 live births in 2018, down from 76 in 2000 - a 49% decline.

"Despite advances in fighting childhood illnesses, infectious diseases remain a leading cause of death for children under the age of 5, particularly in sub-Saharan Africa and Southern Asia," says the report. Pneumonia remains the leading cause of death globally among children under the age of 5, accounting for 15% of deaths. Diarrhoea (8%) and malaria (5%), together with pneumonia, accounted for almost a third of global under-five deaths in 2018. "Malnourished children, particularly those with severe acute malnutrition, have a higher risk of death from these common childhood illnesses. Nutrition-related factors contribute to about 45 per cent of deaths in children under 5 years of age," warns the report. The estimates also show vast inequalities worldwide, with women and children in sub-Saharan Africa facing a higher risk of death than in all other regions. Level of maternal deaths are nearly 50 times higher for women in sub-Saharan Africa compared to high-income countries. In 2018, 1 in 13 children in sub-Saharan Africa died before their fifth birthday - this is 15

[7] https://www.globalagriculture.org/whats-new/news/en/33802.html

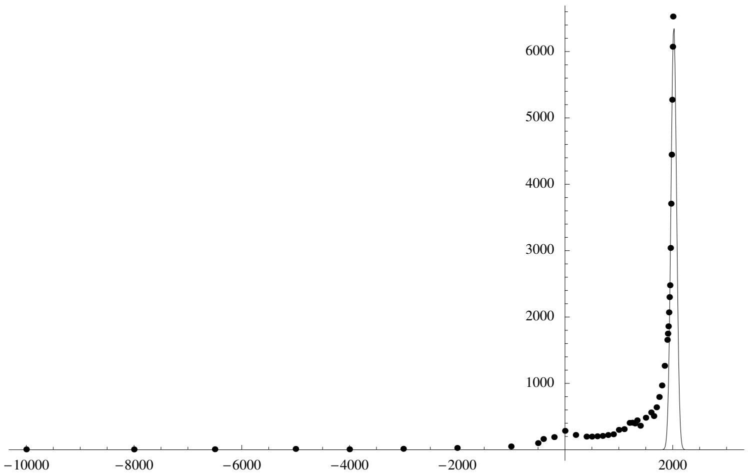

Figure 5.9: **Population growth and fossil fuel use, seen on a time-scale of several thousand years. The dots are population estimates in millions from the US Census Bureau. Fossil fuel use appears as a spike-like curve, rising from almost nothing to a high value, and then falling again to almost nothing in the space of a few centuries. When the two curves are plotted together, the explosive rise of global population is seen to be simultaneous with, and perhaps partially driven by, the rise of fossil fuel use. This raises the question of whether the world's population is headed for a crash when the fossil fuel era has ended.** (Author's own graph)

times higher than the risk a child faces in Europe, where just 1 in 196 children aged less than 5 die.

5.15 Our ecological footprint

Has the number of humans in the world already exceeded the earth's sustainable limits? Will the global population of humans crash catastrophically after having exceeded the carrying capacity of the environment? There is certainly a danger that this will happen - a danger that the 21st century will bring very large scale famines to vulnerable parts of the world, because modern energy-intensive agriculture will be dealt a severe blow by prohibitively high petroleum prices, and because climate change will reduce the world's agricultural output. When the major glaciers in the Himalayas have melted, they will no longer be able to give India and China summer water supplies; rising oceans will drown much agricultural land; and aridity will reduce the output of many regions that now produce much of the world's grain. Falling water tables in overdrawn aquifers, and loss of topsoil will add to the problem. We should be aware of the threat of a serious global food crisis in the 21st century if we are to have a chance of avoiding it.

The term *ecological footprint* was introduced by William Rees and Mathis Wackernagel in the early 1990's to compare demands on the environment with the earth's capacity to regenerate. In 2005, humanity used environmental resources at such a rate that it would take 1.3 earths to renew them. In other words, we have already exceeded the earth's carrying capacity. Since eliminating the poverty that characterizes much of the world today will require more resources per capita, rather than less. it seems likely that in the era beyond fossil fuels, the optimum global population will be considerably less than the present population of the world.

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Chapter 6

THE HEALTH OF OUR OCEANS

6.1 Thermal inertia of the oceans

Calories required to warm a gram of water

We all know that saucepan full of water on the kitchen stove does not start to boil immediately when the heat under it is turned on. In fact, for every gram of water in the saucepan, one calorie is needed for every degree C in temperature rise. If the pan contains a kilogram of water, a kilocalorie is needed to make it warm by 1^oC.

The same principle, vastly scaled up in size, holds for the earth's oceans. When humans "turn on the heat"by releasing greenhouse gases into the atmosphere, the oceans respond very slowly because of the vast amount of energy needed to warm them. The total volume of the oceans is estimated to be 1.35×10^9 km^3 or 1.35×10^{24} cm^3. Thus to warm the earth's oceans by 1^oC requires 1.35×10^{24} calories, and the current imbalance between incoming and outgoing radiation supplies only a small fraction of this amount each year.

This means that even if the CO_2 and other greenhouse gases in our atmosphere were stabilized at their current levels, the oceans would continue to warm for many decades. This does not mean that our efforts to reduce greenhouse gas emissions are futile. We must certainly experience some very unpleasant effects of sea level rise, ocean life destruction and global warming during the next few decades, but how bad these become is up to us.

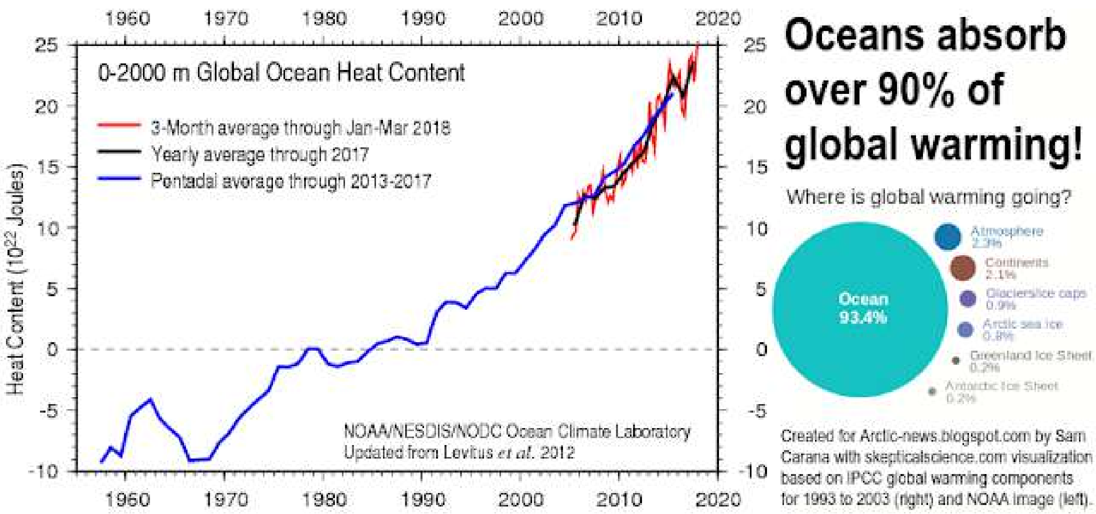

Figure 6.1: **The heat content of the oceans is rapidly increasing.**

6.2 Carbon dioxide content and acidity

Roughly 30-40% of the CO_2 released into the atmosphere by human activities is absorbed by oceans and lakes. Much of the dissolved CO_2 undergoes a reaction with water which converts it into carbonic acid:

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+$$

Between 1751 and 1995 the amount of H^+ ion in ocean surface water is estimated to have increased by 35%. Living organisms are very sensitive to acidity, and today we can observe the alarming death of many forms of marine life, for example the death of coral in the Great Barrier Reef and other coral reef systems. Over a billion people depend on fish from coral reef habitats for protein in their diets.

6.3 Pollution with plastic waste

Our oceans are now massively polluted with carelessly discarded plastic waste. Plastic waste is found in huge quantities on the beaches of the remotest islands and in the blocked digestive systems of dead whales. A recent study [1] found that in 2010, 8 million tonnes of plastic went into our oceans,

The problem of plastic waste in our oceans is connected with the climate emergency, but in an indirect way. Today, most plastics are synthesized from starting chemicals extracted from fossil fuels. But the use of fossil fuels must stop if catastrophic climate change is to be avoided. However, there are new methods for synthesizing biodegradable plastics starting with chemicals extracted from plants.

[1] http://www.abc.net.au/science/articles/2015/02/13/4178113.htm

According to the polymer chemist Professor Andrew Holmes,[2] the world may have to move to fully biodegradable plastics, made out of plants. But these have drawbacks. "The challenge is, is there enough arable land to produce the building blocks of plastic when we also need to produce food?"

In the meantime, he said, we must recycle anything we can.

"Ideally all plastics should be recyclable, but at present that is not the case."

Professor Holmes said plastics that cannot be recycled - such as those used in plastic bags, or expanded polystyrene foam used in coffee cups and packaging around electronic goods - must be responsibly disposed into landfill or by burning.

"The plastic waste in the oceans is disastrous for marine and bird life, and the human race has to avoid disposal of this waste in a way that enables it to enter drains, rivers, and eventually the ocean," he said."

6.4 Overfishing

Like the massive pollution of our oceans with plastic waste, overfishing is only indirectly related to climate change. However, all three phenomena are part of the ecological mega-catastrophe that may result if humans continue to over-exploit and degrade the earth's ecological systems.

Wikipedia's article on overfishing states that "As much as 85% of the world's fisheries may be over-exploited, depleted, fully exploited or in recovery from exploitation....

"With present and forecast world population levels it is not possible to solve the over fishing issue; however, there are mitigation measures that can save selected fisheries and forestall the collapse of others...

"The United Nations Convention on the Law of the Sea treaty deals with aspects of over fishing in articles 61, 62, and 65:

- Article 61 requires all coastal states to ensure that the maintenance of living resources in their exclusive economic zones is not endangered by over-exploitation. The same article addresses the maintenance or restoration of populations of species above levels at which their reproduction may become seriously threatened.

- Article 62 provides that coastal states: "shall promote the objective of optimum utilization of the living resources in the exclusive economic zone without prejudice to Article 61"

- Article 65 provides generally for the rights of, inter alia, coastal states to prohibit, limit, or regulate the exploitation of marine mammals.

"Several scientists have called for an end to subsidies paid to deep sea fisheries. In international waters beyond the 200 nautical mile exclusive economic zones of coastal

[2]University of Melbourne
http://www.abc.net.au/news/science/2017-02-27/plastic-and-plastic-waste-explained/8301316

countries, many fisheries are unregulated, and fishing fleets plunder the depths with state-of-the-art technology. In a few hours, massive nets weighing up to 15 tons, dragged along the bottom by deep-water trawlers, can destroy deep-sea corals and sponge beds that have taken centuries or millennia to grow. The trawlers can target orange roughly, grenadiers, or sharks. These fish are usually long-lived and late maturing, and their populations take decades, even centuries to recover."

6.5 Warming oceans

In its article on "Ocean heat content", Wikipedia stated the following:

"In oceanography and climatology, ocean heat content (OHC) is a term for the energy absorbed by the ocean, which is stored as internal energy or enthalpy. Changes in the ocean heat content play an important role in the sea level rise, because of thermal expansion.

Ocean warming accounts for 90% of the energy accumulation from global warming between 1971 and 2010. About one third of that extra heat has been estimated to propagate to depth below 700 meters.Beyond the direct impact of thermal expansion, ocean warming contributes to an increased rate of ice melting in the fjords of Greenland and Antarctic ice sheets. Warmer oceans are also responsible for coral bleaching."

6.6 Biodiversity and the loss of coral reefs

Coral reefs occupy less than 0.1% 0f the ocean area, but they are the home of 25% of marine species. Because of their great biodiversity, they have been called "the rainforests of the sea".

During the voyage of the Beagle, Charles Darwin developed a theory of how coral reefs are formed, and that theory is considered to be valid today. According to Darwin's ideas, the floor of the Pacific ocean is, in general, sinking. Corals can live only at a limited range of depths. They must be covered by water, even at low tide, but not too deep under water, because sunlight is required for the photosynthesis that the polyp-algae symbionts rely on for energy. Thus as a volcano sinks below the surface with the general sinking of the Pacific ocean floor, the coral reefs grow upward around the perifera to be near to the surface, and thus, according to Darwin, circular coral atolls are formed.

Coral reefs, such as Australia's famous Great Barrier Reef, are under threat from warming oceans and from the acidification that follows from absorption of CO_2. Bleaching and death of corals, underway today, give us yet another reason to urgently address the threat of climate change.

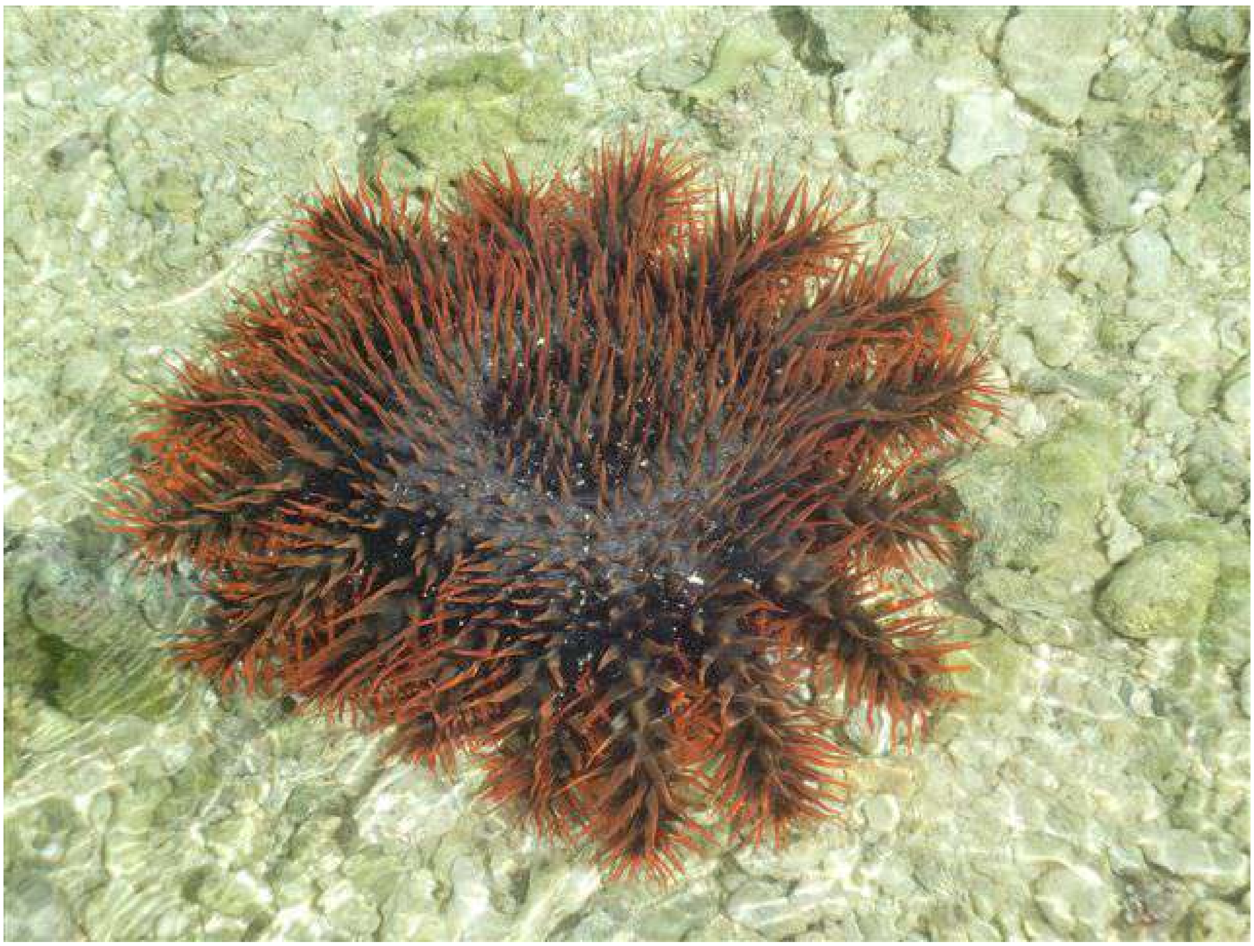

Figure 6.2: **The crown-of-thorns starfish eats coral.**

Figure 6.3: **The overfished giant triton eats the crown-of-thorns starfish.**

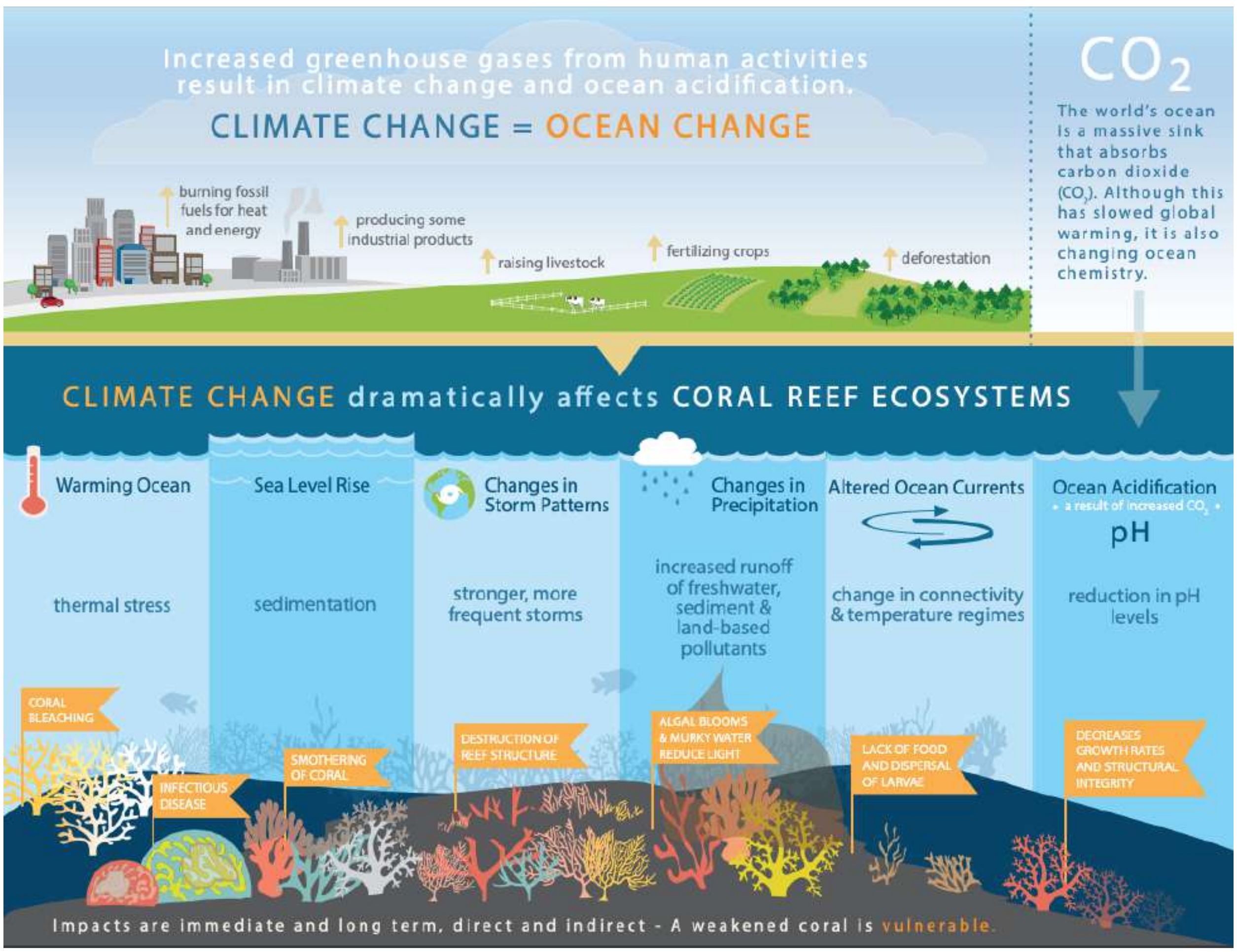

Figure 6.4: **Climate change threats to coral reefs.**

Figure 6.5: **Higher levels of carbon dioxide in the water harms the ability of young clown and damsel fishes to smell and hear.**

6.7 Kelp forests; *My Octopus Teacher*

Like coral reefs, kelp forests around the world form an environment of very high biodiversity. Activists hope that attention will be focused on the need to protect kelp forests by the highly successful Netflix documentary film, *My Octopus Teacher* (2020). The film documents Craig Foster's year-long relationship with an octopus in a South African kelp forest. The film has already won numerous awards, including the British Academy Film Award for Best Documentary, 11 April, 2021, the Critic's Choice Documentary Awards for both Best Cinematography and Best Science/Nature Documentary. The film also won the Pare Lorentz Award, the Grand Teton Award, Best People & Nature Film - Long Form, Best Science in Nature Film - Long Form, and Best Editing at the International Documentary Association Awards, January 16, 2021, as well as numerous other awards.

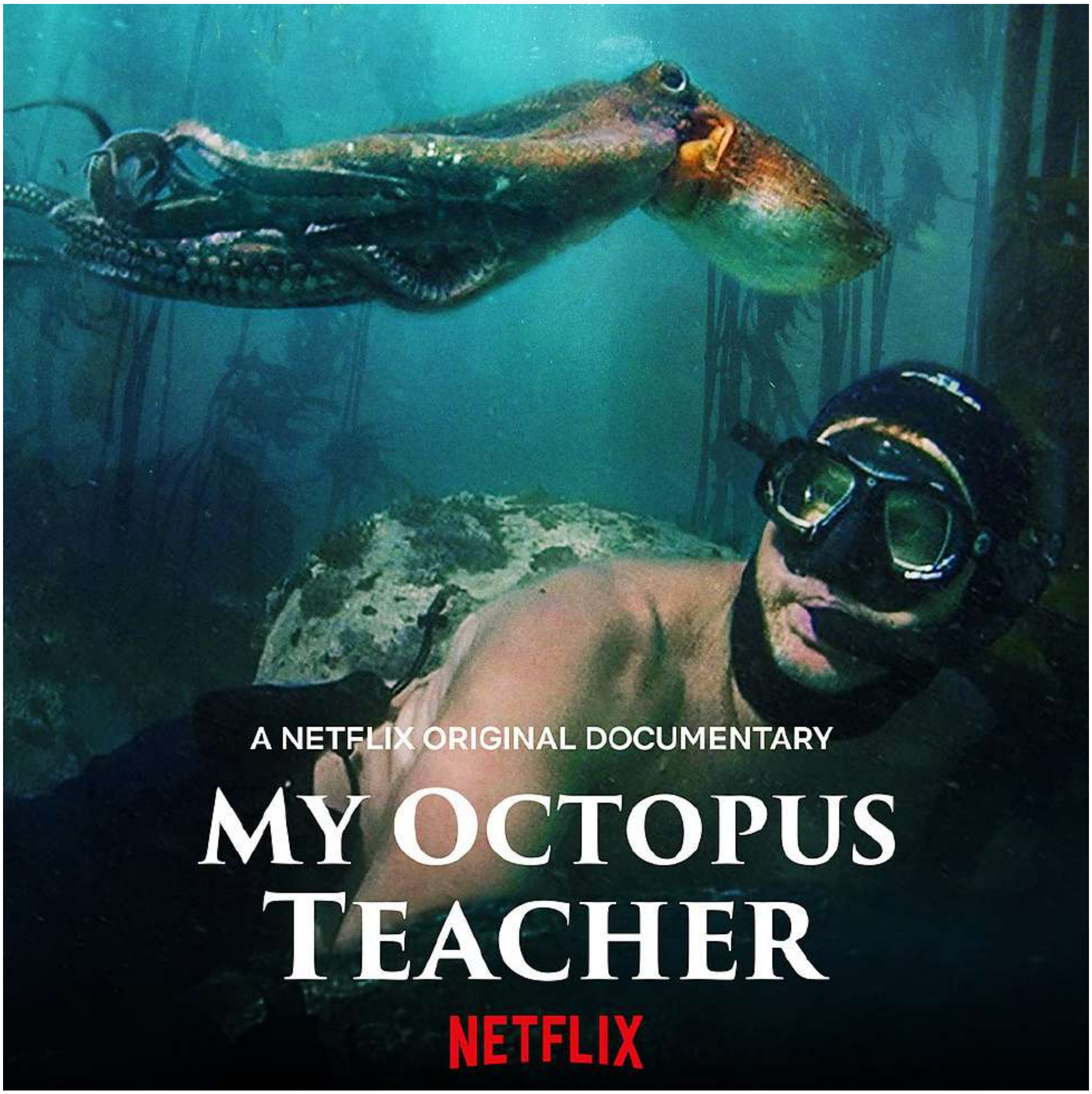

Figure 6.6: **Craig Foster dives with an octopus in the kelp forests off South Africa.**

6.8 The message of Sir David Attenborough

Sir David Attenborough's films which have been broadcast by the BBC

- **Life on Earth (1979)**
- **The Living Planet (1984)**
- **The Trials of Life (1990)**
- **Life in the Freezer (1993)**
- **The Private Life of Plants (1995)**
- **The Life of Birds (1998)**
- **The Life of Mammals (2002)**
- **Life in the Undergrowth (2005)**
- **Life in Cold Blood (2008)**
- **Zoo Quest (1954-63)**
- **The People of Paradise (1960)**
- **The World About Us (1967)**
- **The Miracle of Bali (1969)**
- **The Tribal Eye (1975)**
- **Wildlife on One (1977)**
- **The First Eden (1987)**
- **Lost Worlds, Vanished Lives (1989)**
- **BBC Wildlife Specials (1995-2008)**
- **The Lost Gods of Easter Island (2000)**
- **State of the Planet (2000)**
- **The Blue Planet (2001)**
- **Planet Earth (2006)**
- **Are We Changing Planet Earth? (2006)**
- **Charles Darwin and the Tree of Life (2009)**
- **Nature's Great Events (2009)**
- **Life (2009)**
- **First Life (2010)**
- **Flying Monsters 3D (2010)**
- **The Penguin King (2011)**
- **Kingdom of Plants 3D (2012)**
- **Galapagos 3D (2013)**
- **David Attenborough's Natural History Museum Alive (2014)**
- **Madagascar (2011)**
- **Frozen Planet (2011)**
- **Attenborough: 60 Years in the Wild (2012)**
- **Africa (2013)**
- **David Attenborough's Natural Curiosities (episodes) (2013-)**
- **David Attenborough's Rise of Animals: Triumph of the Vertebrates (2013)**

- When Björk Met Attenborough (2013)
- Life Story (2014) The Hunt (2015)
- Great Barrier Reef (2015)
- Planet Earth II (2016)
- Blue Planet II (2017)
- Dynasties (2018)
- Our Planet (2019)
- Climate Change - The Facts (2019)

Books by Sir David Attenborough

- Zoo Quest to Guyana (1956)
- Zoo Quest for a Dragon (1957) - republished in 1959 to include an additional 85 pages titled Quest for the Paradise Birds
- Zoo Quest in Paraguay (1959)
- Quest in Paradise (1960)
- People of Paradise (1960)
- Zoo Quest to Madagascar (1961)
- Quest Under Capricorn (1963)
- Fabulous Animals (1975)
- The Tribal Eye (1976)
- Life on Earth (1979)
- Discovering Life on Earth (1981)
- The Living Planet (1984)
- The First Eden: The Mediterranean World and Man (1987)
- The Atlas of the Living World (1989)
- The Trials of Life (1990)
- The Private Life of Plants (1994)
- The Life of Birds (1998)
- The Life of Mammals (2002)
- Life on Air: Memoirs of a Broadcaster (2002) - autobiography, revised in 2009
- Life in the Undergrowth (2005)
- Amazing Rare Things: The Art of Natural History in the Age of Discovery (2007) - with Susan Owens, Martin Clayton and Rea Alexandratos
- Life in Cold Blood (2007)
- David Attenborough's Life Stories (2009)
- David Attenborough's New Life Stories (2011)
- Drawn From Paradise: The Discovery, Art and Natural History of the Birds of Paradise (2012) - with Errol Fuller
- Adventures of a Young Naturalist: The Zoo Quest Expeditions (2017)
- Journeys to the Other Side of the World: Further Adventures of a Young Naturalist (2018)

- **Dynasties: The Rise and Fall of Animal Families with Stephen Moss (BBC Books, 2018)**

Sir David Attenborough's almost unbelievably enormous and impressive opus of television programs about the natural world have helped to raise public awareness of the importance of the natural environment. He also has made a number of television programs specifically related to questions such as saving threatened species, the dangers of exploding global human populations, and the destruction of forests for the sake of palm oil plantations.

The Blue Planet

The BBC has recently produced Sir David Attenborough's new series, *Blue Planet II*, which focuss on environmental issues in connection with our oceans.[3]

"My hope is that the world is coming to its senses ... I'm so old I remember a time when ... we didn't talk about climate change, we talked about animals and species extermination," Sir David told Greenpeace in an interview, "For the first time I'm beginning to think there is actually a groundswell, there is a change in the public view. I feel many more people are concerned and more aware of what the problems are. Young people - people who've got 50 years of their life ahead of them - they are thinking they ought to be doing something about this. That's a huge change."

Climate Change, The Facts

Now Sir David Attenborough has completed a new one-hour BBC program on the danger of catastrophic climate change. Here are some excerpts from an April 18 2019 review of the program by Rebecca Nicholson in The Guardian:

The Facts is a rousing call to arms. It is an alarm clock set at a horrifying volume. The first 40 minutes are given over to what Attenborough calls, without hyperbole, "our greatest threat in thousands of years". Expert after expert explains the consequences of rising CO2 levels, on the ice caps, on coastal regions, on weather and wildlife and society itself. The most powerful moments are in footage shot not by expert crews who have spent years on location, but on shaky cameras, capturing the very moment at which the reality of our warming planet struck the person holding the phone. In Cairns, Australia, flying foxes are unable to survive the extreme temperatures; rescuers survey the terrible massacre, and we learn that while 350 were saved, 11,000 died. A man and his son talk through their escape from raging wildfires, over the film they took while attempting to drive through a cavern of blazing red trees. These are horror movies playing out in miniature. It is difficult to watch even five minutes of this and remain somehow neutral, or unconvinced.

[3]http://www.bbcearth.com/blueplanet2/

Figure 6.7: **Speaking at the opening ceremony of COP24, the universally loved and respected naturalist Sir David Attenborough said: "If we don't take action, the collapse of our civilizations and the extinction of much of the natural world is on the horizon."**

Yet as I kept on, scribbling down an increasingly grim list of statistics, most of which I knew, vaguely, though compiled like this they finally sound as dreadful as they truly are - 20 of the warmest years on record happened in the last 22 years; Greenland's ice sheet is melting five times faster than it was 25 years ago - I started to wonder about responsibility, and if and where it would be placed. This would be a toothless film, in the end, if it were hamstrung by political neutrality, and if its inevitable "it's not too late" message rested solely on individuals and what relatively little tweaks we might make as consumers. What about corporations? What about governments?

Then, at that exact moment, having played the despair through to its crescendo, the experts served up unvarnished honesty. They lined up to lay out the facts, plain and simple. Fossil fuel companies are the most profitable businesses man has ever known, and they engage in PR offensives, using the same consultants as tobacco companies, and the resulting uncertainty and denial, designed to safeguard profits, has narrowed our window for action. It is unforgivable. I find it hard to believe that anyone, regardless of political affiliation, can watch footage of Trump calling climate change "a hoax ... a money-making industry" and not be left winded by such staggering ignorance or astonishing deceit, though it is, more likely, more bleakly, a catastrophic combination of the two. At least Nigel Lawson only appears here in archive

Figure 6.8: **Sir David Attenborough testifying at the British Parliament in July, 2019**

footage, and his argument sounds limp, to put it kindly.

Climate Change: The Facts should not have to change minds, but perhaps it will change them anyway, or at least make this seem as pressing as it needs to be. With the Extinction Rebellion protests across London this week, disrupting day-to-day business, and this, on primetime BBC One, maybe the message will filter through. At the very least, it should incite indignation that more was not done, sooner, and then urgency and a decision to both change and push for change at a much higher level. Because there is, for a brief moment, just possibly, still time.

Sir David testifies in Parliament

Referencing the rise of climate science denial in some countries while giving evidence to a committee of MPs in the UK, Attenborough said he was "sorry that there are people in power and internationally, notably the United States, but also in Australia".

Attenborough also said it would be "a very sad day" if President Donald Trump succeeded in withdrawing the US from the Paris Agreement, praising the UN process as an example of international cooperation.

He accused climate science deniers of cherry-picking their data, arguing it isn't proof to find a particular example of where glaciers had grown, rather than shrunk. "The proof is in the graphs, the proof is in the scientific records, the proof is in when you analyze bubbles from the sea ice and glacier ice to show you what has happened to the climate over the years," he added.

Asked if flights would have to become more expensive, to the point that normal families could no longer afford an annual holiday in France or Spain, he replied: "I don't know how you would restrict air travel other than economically, so I am afraid that is the case, yes."

He told the Business, Energy and Industrial Strategy Committee: "There's a huge change in public perception. I suspect we are right now in the beginning of a big change."

Sir David credited young people for bringing about the change, saying the electorate of tomorrow already understand the changes that need to be made.

Some things that Sir David Attenborough has said

The future of life on earth depends on our ability to take action. Many individuals are doing what they can, but real success can only come if there's a change in our societies and our economics and in our politics. I've been lucky in my lifetime to see some of the greatest spectacles that the natural world has to offer. Surely we have a responsibility to leave for future generations a planet that is healthy, inhabitable by all species.

Three and a half million years separate the individual who left these footprints in the sands of Africa from the one who left them on the moon. A mere blink in the eye of evolution. Using his burgeoning intelligence, this most successful of all mammals has exploited the environment to produce food for an ever-increasing population. In spite of disasters when civilizations have over-reached themselves, that process has continued, indeed accelerated, even today. Now mankind is looking for food, not just on this planet but on others. Perhaps the time has now come to put that process into reverse. Instead of controlling the environment for the benefit of the population, perhaps it's time we control the population to allow the survival of the environment.

The growth in human numbers is frightening. I've seen wildlife under mounting human pressure all over the world, and it's not just from human economy or technology. Behind every threat is the frightening explosion in human numbers. I've never seen a problem that wouldn't be easier to solve with fewer people - or harder, and ultimately impossible, with more.

We cannot continue to deny the problem. People have pushed aside the question of population sustainability and not considered it because it is too awkward, embarrassing and difficult. But we have to talk about it.

We are a plague on the Earth. It's coming home to roost over the next 50 years or so. It's not just climate change; it's sheer space, places to grow food for this enormous horde. Either we limit our population growth or the

natural world will do it for us, and the natural world is doing it for us right now.

Extinction: The Facts

In his newest documentary, Sir David presents the stark facts about the current rate of extinction of species.

Here is a quotation from an article by Andrea D. Steffen entitled *Sir David Attenborough's Heartbreaking New Film On Extinction Is A Must See* and published on September 18, 2020[4]:

The now 94-year-old David Attenborough presents us all with a new film called *Extinction: The Facts*. And while Britain's favorite naturalist spent the last seven decades delivering programs about the world's national treasures, this time, it's a hard-hitting documentary warning about species extinction.

The new BBC film begins with heartbreaking footage of devastation with animals battling for survival because of the impact humans inflict on the natural world. It then goes on to explain how serious the state of nature is, why it matters, and what needs to change.

It links the rise of crises like the coronavirus pandemic, food shortage, poverty, and catastrophic weather events to mankind's encroachment on natural habitats and the destruction of biodiversity. It highlights how species extinction undermines human progress but also points out that this desperate situation can be turned around.

Another article reviewing *Extinction: The Facts*

And here is a quotation from an article by Sally Ho entitled *Sir David Attenborough Warns Of Extinction Crisis In Latest BBC Documentary*, published on September 18, 2020[5]:

"In his most recent return to television screens, Sir David Attenborough warns the world about the crisis our planet is in. Premiered on the BBC last weekend, the documentary saw the legendary naturalist deliver a stark message about mass biodiversity loss and the consequences that the world will face as a result.

"Unlike his usual productions that tracks the wonders and beauty of the natural world, Attenborough's latest documentary titled Extinction: The Facts has a radically different tone. 'We are facing a crisis,' he says at the very start of

[4]https://www.intelligentliving.co/david-attenboroughs-film-extinction/

[5]https://www.greenqueen.com.hk/david-attenborough-warning-extinction-crisis-latest-bbc-documentary/

Figure 6.9: **94-year-old Sir David Attenborough issues a stark warning in *Extinction: The Facts.***

the film. 'One that has consequences for us all.'

"Over the course of the one-hour programme, Attenborough takes viewers on a journey through scenes of destruction due to humankind's activities on Earth. In one scene, monkeys jump from trees into a river in order to make a hasty escape from a wildfire, while another sequence shows a koala struggling to find shelter as its natural habitat is ablaze.

"There are an estimated 8 million species inhabiting our planet, the film tells us, and almost one million are now already threatened with extinction. Since the 1970s, vertebrate animals have declined by at least 60%. That's within the past few decades.

"While species do naturally go extinct, Attenborough says that the current rate of extinction is speeding up at such a dramatic rate that it now exceeds the natural course by 100 times - and this figure is still on the rise. In a study published in June this year, scientists said that 500 land animal species are now on the verge of disappearing forever in just 20 years.

"'Over the course of my life I've encountered some of the world's most remark-

able species of animals. Only now do I realise just how lucky I've been - many of these wonders seem set to disappear forever,' he remarks in the film.

"Biodiversity loss will not only mean that we will no longer be able to appreciate the different creatures, flora and fauna in nature, but will also impact our own survival too. The loss of nature's pollinators, such as wild bees, could threaten the crops that we depend on for food, or other plants that help regulate water flow and produce the oxygen we need.

"The coronavirus pandemic is another clear instance of the dangers that come with the rampant destruction of nature and wildlife, a warning many scientists and experts have raised alarm bells about in recent months.

"However, as with all Attenborough's films, Extinction: The Facts ended with a clear message that there is still hope as long as immediate action takes place. 'I may not be here to see it. But if we make the right decisions at this critical moment, we can safeguard our planet's ecosystems, its extraordinary biodiversity and all its inhabitants.'

"Ending with a powerful line, Attenborough said: 'What happens next is up to every one of us'."

A Life On Our Planet

Here is a quotation from an article by Sally Ho entitled *David Attenborough Urges People To Ditch Meat In New Film*, published on 2 September, 2020[6]:

In his upcoming documentary, the legendary Sir David Attenborough calls for a mass dietary shift to plant-based foods in order to re-wild the Earth and save the planet. Called *A Life On Our Planet*, 94-year-old stresses in the film that humans can no longer wait to take drastic action if we are to avoid complete climate and ecological breakdown, and that it has become increasingly clear that the planet simply 'can't support billions of meat-eaters.'

***A Life On Our Planet* is described as Attenborough's most personal exploration into his decades-long career documenting the destruction of wildlife and the environment and his 'witness statement' for the natural world. Set to premiere on Netflix later this year, the WWF and Silverback Films co-produced documentary comes with a bold message from Attenborough that humans must make dramatic changes to our diets in order to save the planet.**

[6]https://www.greenqueen.com.hk/sir-david-attenborough-urges-people-to-ditch-meat-in-new-film/

'I had the most extraordinary life. It's only now I appreciate how extraordinary. The living world is a unique and spectacular marvel,' he says in the movie trailer. 'Yet, the way we humans live on earth is sending it into a decline. Human needs have overrun the world.'

But Attenborough makes clear that this film is not meant to guilt viewers into changing their habits. It's a documentary aimed at showing how each and every one of us can act right now.

'If we act now we can yet put it right. Our planet is headed for disaster. We need to learn how to work with nature rather than against it and I'm going to tell you how,' the wildlife broadcaster, filmmaker and environmentalist said.

His advice to the world, which is revealed in the movie trailer, is to reduce meat consumption or make a full switch to a vegetarian or vegan diet. 'We must radically reduce the way we farm. We must change our diet. The planet can't support billions of meat-eaters.'

While Attenborough himself does not consider himself a 'doctrinaire' vegetarian or vegan, he revealed in a recent interview that he does not have the same appetite for animal meat anymore due to the state of the planet and the realisation of the enormous damage the meat industry has caused.

6.9 Pollution of the Baltic with mercury

The Baltic Sea is among the most polluted ecosystems in the world. It is especially contaminated with organic chemicals and with mercury from the Swedish paper industry. Toxicologists recommend that people in the region surrounding the Baltic should strictly limit their consumption of fish caught in that sea, because of the risk of mercury poisoning. Like other heavy metals, such as lead, mercury accumulates in the body.

6.10 Ocean currents and monsoons

Climate change is increasingly causing ocean currents to change. For example, the current bringing the West African Monsoon has failed in recent years, bringing distress to farmers in the region, who rely on monsoon rains for agriculture. Global warming may also bring ocean current changes that will threaten India's monsoon, on which India's farmers are dependent.

6.11 Algae as a source of food

The amount of fresh water needed to produce food by conventional methods is very large, and limitations on the world's supply of fresh water may also limit our efforts to expand

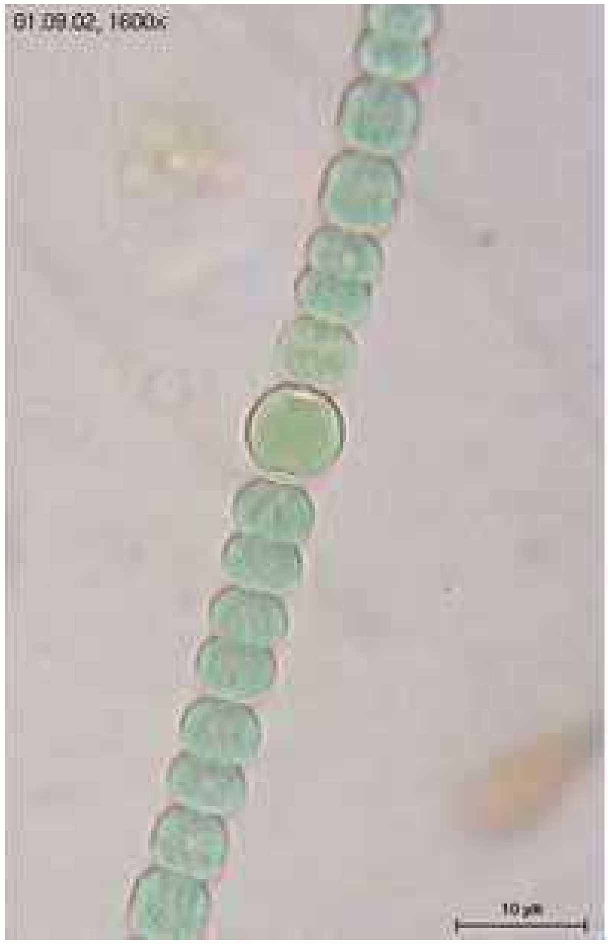

Figure 6.10: **Cyanobacteria (blue-green alga) Anabaena spherica.**

global food production unless new methods are found. One such method is the use of algae as a food source.[7]

Algae can be grown in desert areas in closed waterfilled containers, supplied with carbon dioxide. No water evaporates because the containers are closed, and the conversion of CO_2 into organic matter is an additional benefit. Protein-rich algae are already in baking mixes, cookies, milk, nondairy creamers, vegan eggs, salad dressing, ice-cream, smoothies, and protein powders, to name a few.

[7]See *Algae as a Potential Source of Food and Energy in the Developing Countries*, edited by Alvise Perosa, Guido Bordignon, Giampietro Ravagnan, and Sergey Zinoviev. The pdf file of this book is available for free downloading.

Figure 6.11: **Red alga Polysiphonia spp.**

6.12 Farming the seas

A second way in which the shortage of fresh water for global agriculture can be circumvented is to farm the seas and oceans with crops and other edible species that thrive in salt water. A study by Frank Asche of the University of Stvanger[8] points out that:

- In 1970 aquaculture contributed 5% of the total supply of seafood. In 2005 aquaculture's share was 40% with a production of 62.9 million tonnes.
- Although aquaculture is old, a revolution occurred in the 1970s.
- New technologies and better feeding has led to an enormous increase in production.
- Increasing control with the production process, and semiintensive and intensive farming allow productivity growth and market development.
- Aquaculture is increasingly becoming more like any other crop, and one is Farming the Sea.
- The farming practice varies from highly extensive and very close to hunting and gathering (fisheries) to highly intensive and industrialized.
- It is intensive industrialized farming that allows us to produce much more, and that makes aquaculture a significant source of food.
- This development is still in the early beginning, and there is still a substantial scope for innovation.
- Compared to agriculture, there is still a long way to go.
- Aquaculture is in many ways still in its infancy. There are still only a few species with closed production cycles and selective breeding. There are even fewer species that primarily are sold as fresh packed beside the chicken fillet. There are no farmers that specialize in producing feed for the food crops.
- One can still only observe the first crude attempts to farm the sea.
- We will therefore see a tremendous development during the next decades.

[8]http://www.umb.no/statisk/ior/refsnes/asche.pdf

- Aquaculture is likely to be like any other crop or livestock in the future, because one has the same type of control with the production process. There will be a large range of practices but the large volume producers will be the most intensive.
- Local environmental issues are a management problem and can be solved.

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Chapter 7

SEA LEVEL RISE

7.1 Rate of melting of Arctic ice

Loss of Arctic sea ice

The melting of Arctic sea ice is taking place far more rapidly than was predicted by IPCC reports. David Wasdell, Director of the Apollo-Gaia Project, points out that the observed melting has been so rapid that within less than five years, the Arctic may be free of sea ice at the end of each summer. It will, of course continue to re-freeze during the winters, but the thickness and extent of the winter ice will diminish.

For January 2016, the satellite based data showed the lowest overall Arctic sea ice extent of any January since records begun in 1979. Bob Henson from *Wundergrund* commented: "Hand in hand with the skimpy ice cover, temperatures across the Arctic have been extraordinarily warm for midwinter. Just before New Year's, a slug of mild air pushed temperatures above freezing to within 200 miles of the North Pole. That warm pulse quickly dissipated, but it was followed by a series of intense North Atlantic cyclones that sent very mild air poleward, in tandem with a strongly negative Arctic Oscillation during the first three weeks of the month."

During some periods, Arctic temperatures have been 50^{o}C above normal for the time of year. Equally alarming is the fact that plumes of methane several km^2 in area have been observed bubbling up from the sea floor in the shallow ice-free seas north of Russia.[1]

7.2 Temperature and CO_2 in ice cores

Ice cores from the Greenland and Antarctic ice sheets and from glaciers have yielded valuable data on climate changes as far back as 800,000 years in the past. The ice cores show that there is a close correlation between global temperatures and the CO_2 content

[1] N. Shakhova et al., *Methane release on the Arctic East Siberian shelf* , Geophysical Research Abstracts, Vol.**9**, 01071, 2007

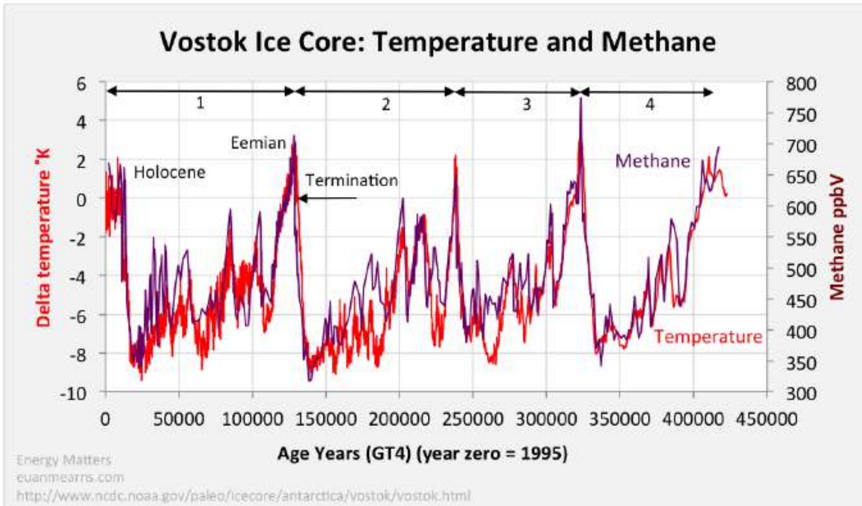

Figure 7.1: **In ice core data, we see a close correlation between temperature and atmospheric CO_2. There is also a close correlation between temperature and atmospheric methane.**

of the atmosphere. The cores also show that climatic changes can take place with great rapidity.

An article by Richard B. Alley in the Proceedings of the National Academy of Science (US) [2] Here is an excerpt from the article:

"Ice-core records show that climate changes in the past have been large, rapid, and synchronous over broad areas extending into low latitudes, with less variability over historical times. These ice-core records come from high mountain glaciers and the polar regions, including small ice caps and the large ice sheets of Greenland and Antarctica.

"As the world slid into and out of the last ice age, the general cooling and warming trends were punctuated by abrupt changes. Climate shifts up to half as large as the entire difference between ice age and modern conditions occurred over hemispheric or broader regions in mere years to decades. Such abrupt changes have been absent during the few key millennia when agriculture and industry have arisen. The speed, size, and extent of these abrupt changes required a reappraisal of climate stability. Records of these changes are especially clear in high-resolution ice cores. Ice cores can preserve histories of local climate (snowfall, temperature), regional (wind-blown dust, sea salt, etc.), and broader (trace gases in the air) conditions, on a common time scale, demonstrating synchrony of climate changes over broad regions."

[2]Proc Natl Acad Sci U S A. 2000 Feb 15; 97(4): 1331-1334. PMCID: PMC34297

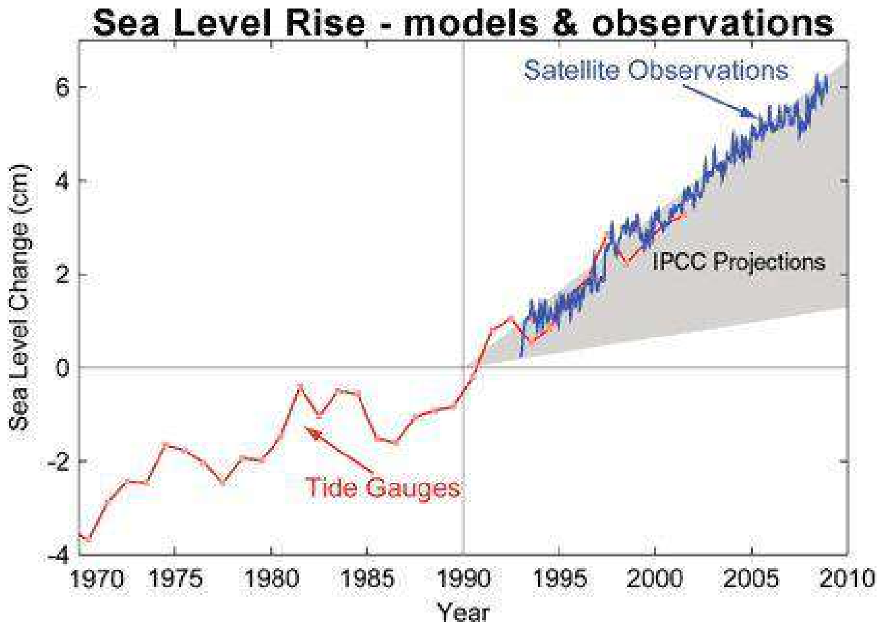

Figure 7.2: **Observed sea-level rise, 1970-2010.**

7.3 Short-term sea level rise

Flooding of coastal cities in the United States

The *National Geographic* recently published an article by Laura Parker entitled “Sea Level Rise Will Flood Hundreds of Cities in the Near Future+.”[3] Here are a few excerpts from the article:

“Sea level rise caused by global warming is usually cast as a doomsday scenario that will play out so far into the future, it’s easy to ignore. Just ask anyone in South Florida, where new construction proceeds apace. Yet already, more than 90 coastal communities in the United States are battling chronic flooding, meaning the kind of flooding that’s so unmanageable it prompts people to move away.

“That number is expected to roughly double to more than 170 communities in less than 20 years.

“Those new statistics, compiled in the first comprehensive mapping of the entire coastline of the Lower 48 states, paint a troubling picture, especially for the East and Gulf coasts, which are home to some of the nation’s most populated areas.

“By the end of the century, chronic flooding will be occurring from Maine to Texas and along parts of the West Coast. It will affect as many as 670 coastal communities, including Cambridge, Massachusetts; Oakland, California; Miami and St. Petersburg, Florida; and four of the five boroughs of New York City. The magnitude of the coming calamity is so great, the ripple effects will reach far into the interior.”

[3]http://news.nationalgeographic.com/2017/07/sea-level-rise-flood-global-warming-science/

Figure 7.3: **Today the beautiful city of Venice is flooded. Tomorrow unless urgent climate action is taken, all coastal cities will be under water.**

Just as an iceberg the size of Delaware broke away from an ice shelf in Antarctica Wednesday, July 12, 2017, scientists released findings that up to 668 U.S. communities could face chronic flooding from rising sea levels by the end of the century.

The Union of Concerned Scientists recently published a report entitled "When Rising Seas Hit Home: Hard Choices Ahead for Hundreds of US Coastal Communities"[4] The report states that "Chronic inundation will dramatically alter the landscape and the livability rise of just three feet would submerge the Maldives and make them uninhabitable of many coastal communities." rise of just three feet would submerge the Maldives and make them uninhabitable

Island nations threatened by rising oceans

The US National Academy of Sciences predictions from 2009 suggest that by 2100, sea level could increase by anywhere from 16 inches to 56 inches, depending how the Earth responds to changing climate.

The Maldives, consisting of over 1,100 islands to the west of India, is the world's lowest-lying nation. On average the islands are only 1.3 meters above sea level. The 325,000 (plus 100,000 expatriate workers who are not counted in the census) residents of the islands are threatened by rising sea levels. A rise of just three feet would submerge the Maldives and

[4]http://www.ucsusa.org/sites/default/files/attach/2017/07/when-rising-seas-hit-home-full-report.pdf

Figure 7.4: **The *World Scientists' Warning of a Climate Emergency* was published in Bioscience on 5 November, 2019. The article states that "Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to 'tell it like it is.' On the basis of this obligation and the graphical indicators presented below, we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency...Despite 40 years of global climate negotiations... we have generally conducted business as usual and have largely failed to address this predicament."**

make them uninhabitable. Many island nations in the Pacific are also severely threatened by sea level rise.

Displacement of populations in Southeast Asia

A World Bank press release has stated that "Bangladesh will be among the most affected countries in South Asia by an expected 2^{o}C rise in the world's average temperatures in the next decades, with rising sea levels and more extreme heat and more intense cyclones threatening food production, livelihoods, and infrastructure as well as slowing the reduction on poverty, according to a new scientific report released today by the World Bank Group.

" 'Bangladesh faces particularly severe challenges with climate change threatening its impressive progress in overcoming poverty,' said Johannes Zutt, World Bank Country Director for Bangladesh and Nepal. 'Bangladesh has demonstrated itself as a leader in moving the climate change agenda forward'-

"In Bangladesh, 40% of productive land is projected to be lost in the southern region of Bangladesh for a 65cm sea level rise by the 2080s. About 20 million people in the coastal areas of Bangladesh are already affected by salinity in drinking water. Rising sea levels and more intense cyclones and storm surges could intensify the contamination of groundwater and surface water causing more diarrhea outbreak."

Important rice-growing river delta regions of Viet Nam will also be lost during the present century.

Effects on the Netherlands, Danish islands, and Venice

Although the Netherlands, the Danish islands and Venice have had many years of experience in coping with floods due to high sea levels and storm surges, these European areas may have difficulties during the present century.

Greenland's icecap is melting much faster than was predicted by the IPCC, and sea level rise may exceed 100 cm. before 2100. Hurricanes are also becoming more severe, as has already been shown by Katrina and Sandy. Future hurricanes hitting Europe's Atlantic coasts will produce dangerous storm surges. In Venice, the danger from hurricanes is less severe, but Venice already experiences severe flooding and the rise of sea levels during the present century may endanger the priceless cultural monuments of the famous ancient city.

7.4 Long-term sea level rise

A 2012 article by Jevrejeva, S., Moore, J. C. and Grinsted, A. in the in the Journal of Global and Planetary Change[5] deals with sea level rise until 2500. Of course, the long-term future runs over hundreds of millennia, but nevertheless, the article, entitled "Sea level projections to AD2500 with a new generation of climate change scenarios" is of interest.

[5]Volumes 80-81, January 2012, Pages 14.20

The article states that "Sea level rise over the coming centuries is perhaps the most damaging side of rising temperature. The economic costs and social consequences of coastal flooding and forced migration will probably be one of the dominant impacts of global warming. To date, however, few studies on infrastructure and socio-economic planning include provision for multi-century and multi-meter rises in mean sea level...

"We estimate sea level rise of 0.57 - 1.10 m by 2100 with four new RCP scenarios. Sea level will continue to rise for several centuries reaching 1.84 - 5.49 m by 2500. Due to long response time most rise is expected after stabilization of forcing. 200-400 years will require dropping the rate to the 1.8 mm/yr- 20th century average."

According to an article published by the Potsdam Institute for Climate Impact Research [6] "The Greenland ice sheet is likely to be more vulnerable to global warming than previously thought. The temperature threshold for melting the ice sheet completely is in the range of 0.8 to 3.2 degrees Celsius global warming, with a best estimate of 1.6 degrees above pre-industrial levels, shows a new study by scientists from the Potsdam Institute for Climate Impact Research (PIK) and the Universidad Complutense de Madrid. Today, already 0.8 degrees global warming has been observed. Substantial melting of land ice could contribute to long-term sea-level rise of several meters and therefore it potentially affects the lives of many millions of people.

"The time it takes before most of the ice in Greenland is lost strongly depends on the level of warming. 'The more we exceed the threshold, the faster it melts,' says Alexander Robinson, lead-author of the study now published in Nature Climate Change. In a business-as-usual scenario of greenhouse-gas emissions, in the long run humanity might be aiming at 8 degrees Celsius of global warming. This would result in one fifth of the ice sheet melting within 500 years and a complete loss in 2000 years, according to the study. 'This is not what one would call a rapid collapse,' says Robinson. 'However, compared to what has happened in our planet's history, it is fast. And we might already be approaching the critical threshold.'

"In contrast, if global warming would be limited to 2 degrees Celsius, complete melting would happen on a timescale of 50.000 years. Still, even within this temperature range often considered a global guardrail, the Greenland ice sheet is not secure. Previous research suggested a threshold in global temperature increase for melting the Greenland ice sheet of a best estimate of 3.1 degrees, with a range of 1.9 to 5.1 degrees. The new study's best estimate indicates about half as much.

"'Our study shows that under certain conditions the melting of the Greenland ice sheet becomes irreversible. This supports the notion that the ice sheet is a tipping element in the Earth system,' says team-leader Andrey Ganopolski of PIK. 'If the global temperature significantly overshoots the threshold for a long time, the ice will continue melting and not re-grow - even if the climate would, after many thousand years, return to its preindustrial state- This is related to feedbacks between the climate and the ice sheet: The ice sheet is over 3000 meters thick and thus elevated into cooler altitudes. When it melts

[6] https://www.pik-potsdam.de/news/press-releases/archive/2012/gronlands-eismassen-konnten-komplett-schmelzen-bei-1-6-grad-globaler-erwarmung

its surface comes down to lower altitudes with higher temperatures, which accelerates the melting. Also, the ice reflects a large part of solar radiation back into 'Our study shows that under certain conditions the melting of the Greenland ice sheet becomes irreversible. This supports the notion that the ice sheet is a tipping element in the Earth system,' says team-leader Andrey Ganopolski of PIK.'If the global temperature significantly overshoots the threshold for a long time, the ice will continue melting and not re-grow - even if the climate would, after many thousand years, return to its preindustrial state.' This is related to feedbacks between the climate and the ice sheet: The ice sheet is over 3000 meters thick and thus elevated into cooler altitudes. When it melts its surface comes down to lower altitudes with higher temperatures, which accelerates the melting. Also, the ice reflects a large part of solar radiation back into space. When the area covered by ice decreases, more radiation is absorbed and this adds to regional warming.space. When the area covered by ice decreases, more radiation is absorbed and this adds to regional warming."

7.5 Populations displaced by sea level rise

In a recent article[7] discussed the long-term effects of sea level rise and the massive refugee crisis that it might create. By 2060, about 1.4 billion people could be climate change refugees, according to the paper, and that number could reach 2 billion by 2100.

The lead author, Prof. Emeritus Charles Geisler of Cornell University says: "The colliding forces of human fertility, submerging coastal zones, residential retreat, and impediments to inland resettlement is a huge problem. We offer preliminary estimates of the lands unlikely to support new waves of climate refugees due to the residues of war, exhausted natural resources, declining net primary productivity, desertification, urban sprawl, land concentration, 'paving the planet' with roads and greenhouse gas storage zones offsetting permafrost melt."

We should notice that Prof. Geisler's estimate of 2 billion climate refugees by 2100 includes all causes, not merely sea level rise. However, the number of refugees from sea level rise alone will be very large, since all the world's coastal cities, and many river deltas will be at risk.

7.6 Populations displaced by drought and famine

Climate change could produce a refugee crisis that is "unprecedented in human history", Barack Obama has warned as he stressed global warming was the most pressing issue of the age.

Speaking at an international food conference in Milan, the former US President said rising temperatures were already making it more difficult to grow crops and rising food prices were "leading to political instability".

[7]Geisler C. et al,, *Impediments to inland resettlement under conditions of accelerated sea level rise* , Land Use Policy, Vol **55**, July 2017, Pages 322-330

If world leaders put aside "parochial interests" and took action to reduce greenhouse gas emissions by enough to restrict the rise to one or two degrees Celsius, then humanity would probably be able to cope.

Failing to do this, Mr. Obama warned, increased the risk of "catastrophic" effects in the future, "not only real threats to food security, but also increases in conflict as a consequence of scarcity and greater refugee and migration patterns".

"If you think about monsoon patterns in the Indian subcontinent, maybe half a billion people rely on traditional rain patterns in those areas,"

Suggestions for further reading

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Chapter 8

HYDROELECTRIC POWER, AND OCEAN ENERGY

8.1 Hydroelectric power

In 2015, hydroelectric power supplied 16.6% of all electrical power, and 70% of the electrical power generated from renewable energy. In the developed countries, the potential for increasing this percentage is small, because most of the suitable sites for dams are already in use. Mountainous regions of course have the greatest potential for hydroelectric power, and this correlates well with the fact that virtually all of the electricity generated in Norway comes from hydro, while in Iceland and Austria the figures are respectively 83% and 67%. Among the large hydroelectric power stations now in use are the La Grande complex in Canada (16 GW_e) and the Itapú station on the border between Brazil and Paraguay (14 GW_e). The Three Gorges Dam in China produces 18.2 GW_e.

Even in regions where the percentage of hydro in electricity generation is not so high, it plays an important role because hydropower can be used selectively at moments of peak demand. Pumping of water into reservoirs can also be used to store energy.

The creation of lakes behind new dams in developing countries often involves problems, for example relocation of people living on land that will be covered by water, and loss of the land for other purposes[1]. However the energy gain per unit area of lake can be very large - over 100 W_e/m^2. Fish ladders can be used to enable fish to reach their spawning grounds above dams. In addition to generating electrical power, dams often play useful roles in flood control and irrigation.

At present, hydroelectric power is used in energy-intensive industrial processes, such as the production of aluminum. However, as the global energy crisis becomes more severe, we can expect that metals derived from electrolysis, such as aluminum and magnesium, will be very largely replaced by other materials, because the world will no longer be able to afford the energy needed to produce them.

[1]Over a million people were displaced by the construction of the Three Gorges Dam in China, and many sites of cultural value were lost

Table 8.1: Technical potential and utilization of hydropower. (Data from World Energy Council, 2003.)

Region	Technical potential	Annual output	Percent used
Asia	0.5814 TW_e	0.0653 TW_e	11%
S. America	0.3187 TW_e	0.0579 TW_e	18%
Europe	0.3089 TW_e	0.0832 TW_e	27%
Africa	0.2155 TW_e	0.0091 TW_e	4%
N. America	0.1904 TW_e	0.0759 TW_e	40%
Oceania	0.0265 TW_e	0.0046 TW_e	17%
World	1.6414 TW_e	0.2960 TW_e	18%

Figure 8.1: **Hydroelectric power does not suffer from the problem of intermittency, but may sometimes produce undesirable social and ecological impacts.**

8.2 Tidal power

The twice-daily flow of the tides can be harnessed to produce electrical power. Ultimately tidal energy comes from the rotation of the earth and its interaction with the moon's gravitational field. The earth's rotation is very gradually slowing because of tidal friction, and the moon is gradually receding from the earth, but this process will take such an extremely long time that tidal energy can be thought of as renewable.

There are two basic methods for harnessing tidal power. One can build barriers that create level differences between two bodies of water, and derive hydroelectric power from the head of water thus created. Alternatively it is possible to place the blades of turbines in a tidal stream. The blades are then turned by the tidal current in much the same way that the blades of a wind turbine are turned by currents of air.

There are plans for using the second method on an extremely large scale in Cook Strait, near New Zealand. A company founded by David Beach and Chris Bathurst plans to anchor 7,000 turbines to the sea floor of Cook Strait in such a way that they will float 40 meters below the surface. Beach and Bathurst say that in this position, the turbines will be safe from the effects of earthquakes and storms. The tidal flow through Cook Strait is so great that the scheme could supply all of New Zealand's electricity if the project is completed on the scale visualized by its founders.

Choosing the proper location for tidal power stations is important, since the height of tides depends on the configuration of the land. For example, tides of 17 meters occur in the Bay of Fundy, at the upper end of the Gulf of Maine, between New Brunswick and Nova Scotia. Here tidal waves are funneled into the bay, creating a resonance that results in the world's greatest level difference between high an low tides. An 18 MW_e dam-type tidal

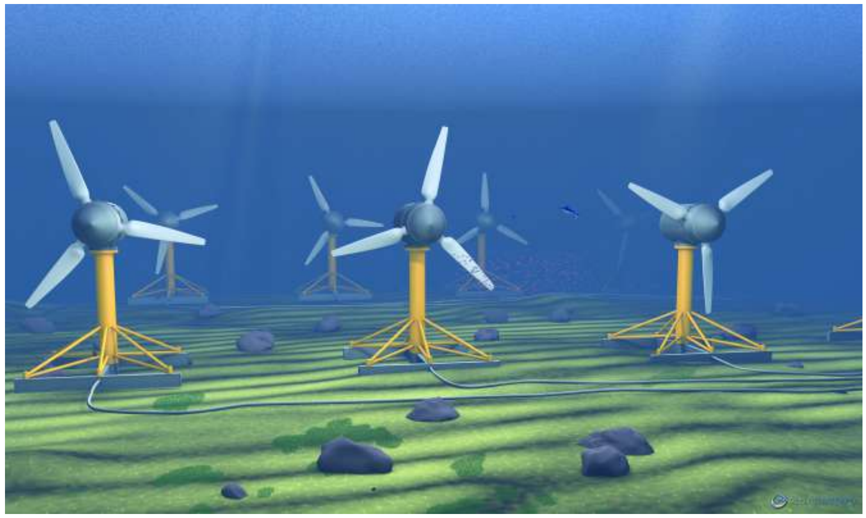

Figure 8.2: **Underwater turbines can make use of the energy of ocean currents.**

power generation station already exists at Annapolis River, Nova Scotia, and there are proposals to increase the use of tidal power in the Bay of Fundy. Some proposals involve turbines in the tidal stream, similar to those proposed for use in the Cook Strait.

In the future, favorable locations for tidal power may be exploited to their full potentialities, even thought the output of electrical energy exceeds local needs. The excess energy can be stored in the form of hydrogen (see below) and exported to regions deficient in renewable energy resources.

8.3 Wave energy

At present, the utilization of wave energy is in an experimental stage. In Portugal, there are plans for a wave farm using the Pelamis Wave Energy Converter. The Pelamis is a long floating tube with two or more rigid sections joined by hinges. The tube is tethered with its axis in the direction of wave propagation. The bending between sections resulting from passing waves is utilized to drive high pressure oil through hydraulic motors coupled to electrical generators. Each wave farm in the Portuguese project is planned to use three Pelamis converters, each capable of producing 750 kW_e. Thus the total output of each wave farm will be 2.25 MW_e.

Another experimental wave energy converter is Salter's Duck, invented in the 1970's by Prof. Stephen Salter of the University of Edinburgh, but still being developed and improved. Like the Pelamis, the Duck is also cylindrical in shape, but the axis of the cylinder is parallel to the wave front, i.e. perpendicular to the direction of wave motion. A floating cam, attached to the cylinder, rises and falls as a wave passes, driving hydraulic motors within the cylinder. Salter's Duck is capable of using as much as 65% of the wave's energy.

Figure 8.3: **The Pelamis wave energy transformer floats on the ocean like a giant sea snake. It consists of several segments which move against each other and build up hydraulic pressure. This in turn drives a turbine. A new Pelamis generation is currently under construction.**

The energy potentially available from waves is very large, amounting to as much as 100 kilowatts per meter of wave front in the best locations.

8.4 Ocean thermal energy conversion

In tropical regions, the temperature of water at the ocean floor is much colder than water at the surface. In ocean thermal energy conversion, cold water is brought to the surface from depths as great as 1 km, and a heat engine is run between deep sea water at a very low temperature and surface water at a much higher temperature.

According to thermodynamics, the maximum efficiency of a heat engine operating between a cold reservoir at the absolute temperature T_C and a hot reservoir at the absolute temperature T_H is given by 1-T_C/T_H. In order to convert temperature on the centigrade scale to absolute temperature (degrees Kelvin) one must add 273 degrees. Thus the maximum efficiency of a heat engine operating between water at the temperature of 25 ^{o}C and water at 5 ^{o}C is 1-(5+273)/(25+273)=0.067 = 6.7%. The efficiency of heat engines is always less than the theoretical maximum because of various losses, such as the loss due to friction. The actual overall efficiencies of existing ocean thermal energy conversion (OTEC) stations are typically 1-3%. On the other hand, the amount of energy potentially available from differences between surface and bottom ocean temperatures is extremely large.

Since 1974, OTEC research has been conducted by the United States at the Natural Energy Laboratory of Hawaii. The Japanese government also supports OTEC research, and India has established a 1 MW_e OTEC power station floating in the ocean near to Tamil Nadu.

Renewable energy from evaporation

A September 26, 2017 article by Ahmet-Hamdi Cavusoglu et al. in *Nature Communications* points to evaporation as a future source of renewable energy. Here are some excerpts from the article:

"About 50% of the solar energy absorbed at the Earth's surface drives evaporation, fueling the water cycle that affects various renewable energy resources, such as wind and hydropower. Recent advances demonstrate our nascent ability to convert evaporation energy into work, yet there is little understanding about the potential of this resource.

"Here we study the energy available from natural evaporation to predict the potential of this ubiquitous resource. We find that natural evaporation from open water surfaces could provide power densities comparable to current wind and solar technologies while cutting evaporative water losses by nearly half. We estimate up to 325 GW of power is potentially available in the United States. Strikingly, water's large heat capacity is sufficient to control power output by storing excess energy when demand is low, thus reducing intermittency and improving reliability. Our findings motivate the improvement of materials and devices that convert energy from evaporation...

"Recent advances in water responsive materials and devices demonstrate the ability to convert energy from evaporation into work. These materials perform work through a cycle of absorbing and rejecting water via evaporation. These water-responsive materials can be incorporated into evaporation-driven engines that harness energy when placed above a body of evaporating water. With improvements in energy conversion efficiency, such devices could become an avenue to harvest energy via natural evaporation from water reservoirs."

Ozgur Sahin, a biophysicist at Columbia, has developed technology that uses spores from the harmless soil-dwelling bacterium *B. subtilis* to absorb and release water when the relative humidity of the surrounding air changes. At high humidity, the spores take in water and expand, and at low humidity they release water and contract, acting like a muscle.

8.5 Hydrogen technologies

Electrolysis of water

When water containing a little acid is placed in a container with two electrodes and subjected to an external direct current voltage greater than 1.23 Volts, bubbles of hydrogen gas form at one electrode (the cathode), while bubbles of oxygen gas form at the other electrode (the anode). At the cathode, the half-reaction

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \qquad E^0 = -1.23\ Volts$$

takes place, while at the anode, the half-reaction

$$4H^+(aq) + 4e^- \rightarrow 2H_2(g) \qquad E^0 = 0$$

occurs.

Half-reactions differ from ordinary chemical reactions in containing electrons either as reactants or as products. In electrochemical reactions, such as the electrolysis of water, these electrons are either supplied or removed by the external circuit. When the two half-reactions are added together, we obtain the total reaction:

$$2H_2O(l) \rightarrow O_2(g) + 2H_2(g) \qquad E^0 = -1.23\ Volts$$

Notice that $4H^+$ and $4e^-$ cancel out when the two half-reactions are added. The total reaction does not occur spontaneously, but it can be driven by an external potential E, provided that the magnitude of E is greater than 1.23 volts.

When this experiment is performed in the laboratory, platinum is often used for the electrodes, but electrolysis of water can also be performed using electrodes made of graphite.

Electrolysis of water to produce hydrogen gas has been proposed as a method for energy storage in a future renewable energy system. For example, it might be used to store energy generated by photovoltaics in desert areas of the world. Compressed hydrogen gas could then be transported to other regions and used in fuel cells. Electrolysis of water and storage of hydrogen could also be used to solve the problem of intermittency associated with wind energy or solar energy.

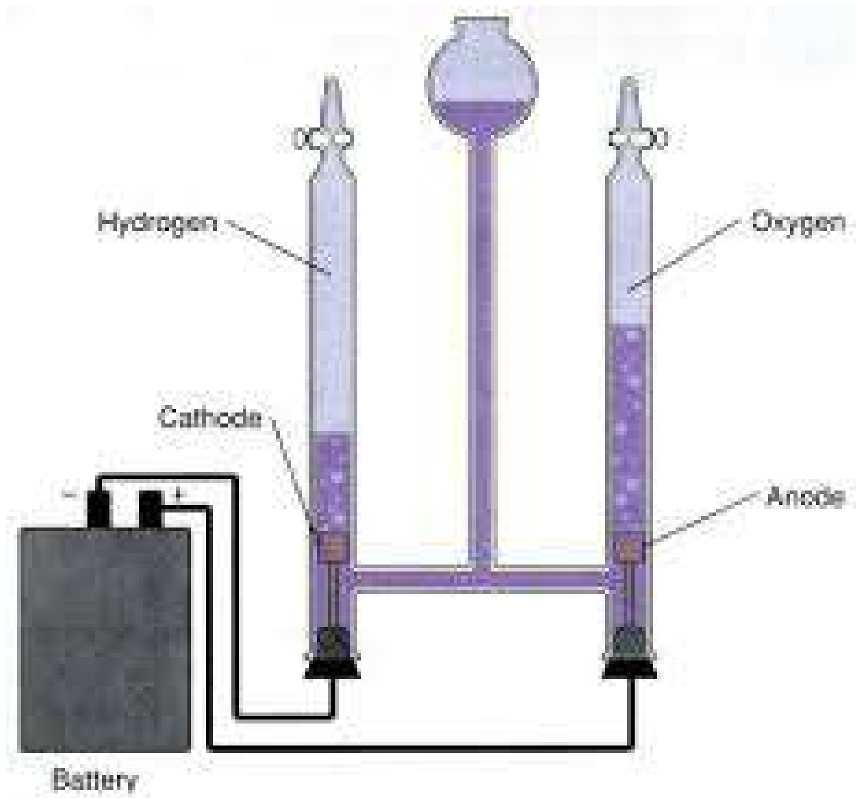

Figure 8.4: **Electrolysis of water.**

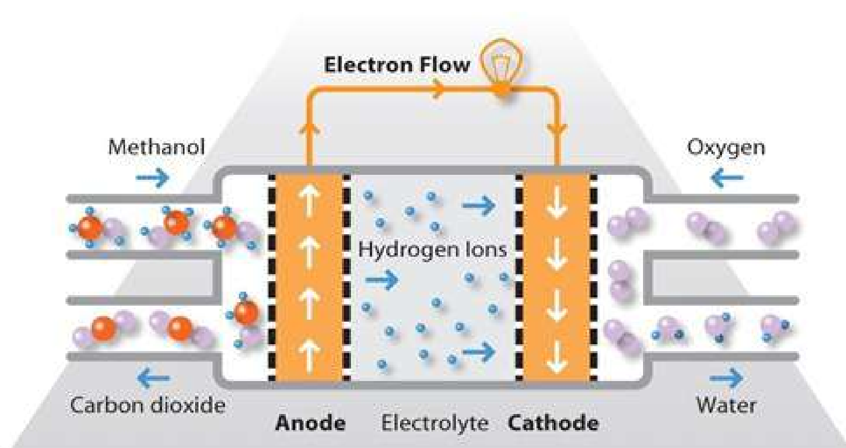

Figure 8.5: **A methanol fuel cell.**

Half reactions

Chemical reactions in which one or more electrons are transferred are called *oxidation-reduction reactions*. Any reaction of this type can be used in a fuel cell. As an example, we can consider the oxidation-reduction reaction in which solid lithium metal reacts with fluorine gas;

$$2Li_{(s)} + F_{2(g)} \to 2LiF_{(s)}$$

This reaction can be split into two half-reactions,

$$Li_{(s)} \to Li^+ + e^- \qquad\qquad E_0 = -3.040\ V$$

and

$$F_{2(g)} \to 2F^+ + 2e^- \qquad\qquad E_0 = 2.87\ V$$

The quantity E_0 which characterizes these half-reactions is called *standard potential* of the half-reaction, and it is measured in Volts. If the oxidation-reduction reaction is used as the basis of a fuel cell, the voltage of the cell is the difference between the two standard potentials. In the lithium fluoride example, it is

$$2.87\ V - (-3.040\ V) = 5.91\ V$$

Here are a few more half-reactions and their standard potentials:

$$\begin{array}{cl}
K^+ + e^- \to\ K_{(s)} & E_0 = -2.924\ V \\
Na^+ + e^- \to Na_{(s)} & E_0 = -2.7144\ V \\
2H_2O + 2e^- \to H_20 + 2OH^- & E_0 = -0.828\ V \\
Zn^{2+} + 2e^- \to Zn_{(s)} & E_0 = -0.7621\ V \\
Fe^{2+} + 2e^- \to Fe_{(s)} & E_0 = -0.440\ V \\
Pb^{2+} + 2e^- \to Pb_{(s)} & E_0 = -0.1266\ V \\
2H^+ + 2e^- \to H_{2(g)} & E_0 \equiv 0.0000\ V \\
Cu^{2+} + 2e^- \to Cu_{(s)} & E_0 = +0.3394\ V \\
I_{2(s)} + 2e^- \to 2I^- & E_0 = +0.535\ V \\
Fe^{3+} + e^- \to Fe^{2+} & E_0 = +0.769\ V \\
Br_{2(l)} + 2e^- \to 2Br^- & E_0 = +1.0775\ V \\
O_{2(g)} + 4H^+ + 4e^- \to 2H_2O & E_0 = +1.2288\ V \\
Cl_{2(g)} + 2e^- \to 2Cl^- & E_0 = +1.3601\ V
\end{array}$$

Fuel cells are closely related to storage batteries. Essentially, when we recharge a storage battery we are just running a fuel cell backwards, applying an electrical potential which is sufficient to make a chemical reaction run in a direction opposite to the way that it would run spontaneously. When the charged battery is afterwards used to drive a vehicle or to power an electronic device, the reaction runs in the spontaneous direction, but the energy of the reaction, instead of being dissipated as heat, drives electrons through an external circuit and performs useful work.

8.6 Against nuclear power generation

No discussion of renewable energy is complete without some mention of the dangers of nuclear power generation. Because of the threat of catastrophic climate change, many voices have been raised proposing that since fossil fuels must be quickly abandoned, nuclear power generation should be "given a second chance". However, as discussed below, this would be prohibitively dangerous.

The dangers of nuclear power generation are exemplified by the Chernobyl disaster: On the 26th of April, 1986, during the small hours of the morning, the staff of the Chernobyl nuclear reactor in Ukraine turned off several safety systems in order to perform a test. The result was a core meltdown in Reactor 4, causing a chemical explosion that blew off the reactor's 1,000-ton steel and concrete lid. 190 tons of highly radioactive uranium and graphite were hurled into the atmosphere. The resulting radioactive fallout was 200 times greater than that caused by the nuclear bombs that destroyed Hiroshima and Nagasaki. The radioactive cloud spread over Belarus, Ukraine, Russia, Finland, Sweden and Eastern Europe, exposing the populations of these regions to levels of radiation 100 times the normal background. Ultimately, the radioactive cloud reached as far as Greenland and parts of Asia.

The exact number of casualties resulting from the Chernobyl meltdown is a matter of controversy, but according to a United Nations report, as many as 9 million people have been adversely affected by the disaster. Since 1986, the rate of thyroid cancer in affected areas has increased ten-fold. An area of 155,000 square kilometers (almost half the size of Italy) in Belarus, Ukraine and Russia is still severely contaminated. Even as far away as Wales, hundreds of farms are still under restrictions because of sheep eating radioactive grass.

Public opinion turned against nuclear power generation as a result of the Chernobyl disaster. Had the disaster taken place in Western Europe or North America, its effect on public opinion would have been still greater. Nevertheless, because of the current energy crisis, and because of worries about global warming, a number of people are arguing that nuclear energy should be given a second chance. The counter-argument is that a large increase in the share of nuclear power in the total spectrum of energy production would have little effect on climate change but it would involve unacceptable dangers, not only dangers of accidents and dangers associated with radioactive waste disposal, but above all, dangers of proliferation of nuclear weapons.

Of the two bombs that destroyed Hiroshima and Nagasaki, one made use of the rare isotope of uranium, U-235, while the other used plutonium. Both of these materials can be made by a nation with a nuclear power generation program.

Reactors and nuclear weapons

Uranium has atomic number 92, i.e., a neutral uranium atom has a nucleus containing 92 positively-charged protons, around which 92 negatively-charged electrons circle. All of the isotopes of uranium have the same number of protons and electrons, and hence the same chemical properties, but they differ in the number of neutrons in their nuclei. For example, the nucleus of U-235 has 143 neutrons, while that of U-238 has 146. Notice that 92+143=235, while 92+146=238. The number written after the name of an element to specify a particular isotope is the number of neutrons plus the number of protons. This is called the "nucleon number", and the weight of an isotope is roughly proportional to it. This means that U-238 is slightly heavier than U-235. If the two isotopes are to be separated, difficult physical methods dependent on mass must be used, since their chemical properties are identical. In natural uranium, the amount of the rare isotope U-235 is only 0.7 percent.

A paper published in 1939 by Niels Bohr and John A. Wheeler indicated that it was the rare isotope of uranium, U-235, that undergoes fission. A bomb could be constructed, they pointed out, if enough highly enriched U-235 could be isolated from the more common isotope, U-238. Calculations later performed in England by Otto Frisch and Rudolf Peierls showed that the "critical mass" of highly enriched uranium needed is quite small: only a few kilograms.

The Bohr-Wheeler theory also predicted that an isotope of plutonium, Pu-239, should be just as fissionable as U-235[2]. Instead of trying to separate the rare isotope, U-235, from the common isotope, U-238, physicists could just operate a nuclear reactor until a sufficient amount of Pu-239 accumulated, and then separate it out by ordinary chemical means.

Thus in 1942, when Enrico Fermi and his coworkers at the University of Chicago produced the world's first controlled chain reaction within a pile of cans containing ordinary (nonenriched) uranium powder, separated by blocks of very pure graphite, the chain-reacting pile had a double significance: It represented a new source of energy for mankind, but it also had a sinister meaning. It represented an easy path to nuclear weapons, since one of the by-products of the reaction was a fissionable isotope of plutonium, Pu-239. The bomb dropped on Hiroshima in 1945 used U-235, while the Nagasaki bomb used Pu-239.

By reprocessing spent nuclear fuel rods, using ordinary chemical means, a nation with a power reactor can obtain weapons-usable Pu-239. Even when such reprocessing is performed under international control, the uncertainty as to the amount of Pu-239 obtained is large enough so that the operation might superficially seem to conform to regulations while still supplying enough Pu-239 to make many bombs.

The enrichment of uranium[3] is also linked to reactor use. Many reactors of modern design make use of low enriched uranium (LEU) as a fuel. Nations operating such a reactor may claim that they need a program for uranium enrichment in order to produce LEU for fuel rods. However, by operating their ultracentrifuges a little longer, they can easily produce highly enriched uranium (HEU), i.e., uranium containing a high percentage of the

[2]Both U-235 and Pu-239 have odd nucleon numbers. When U-235 absorbs a neutron, it becomes U-236, while when Pu-239 absorbs a neutron it becomes Pu-240. In other words, absorption of a neutron converts both these species to nuclei with even nucleon numbers. According to the Bohr-Wheeler theory, nuclei with even nucleon numbers are especially tightly-bound. Thus absorption of a neutron converts U-235 to a highly-excited state of U-236, while Pu-239 is similarly converted to a highly excited state of Pu-240. The excitation energy distorts the nuclei to such an extent that fission becomes possible.

[3]i.e. production of uranium with a higher percentage of U-235 than is found in natural uranium

rare isotope U-235, and therefore usable in weapons.

Known reserves of uranium are only sufficient for the generation of 8×10^{20} joules of electrical energy [4], i.e., about 25 TWy. It is sometimes argued that a larger amount of electricity could be obtained from the same amount of uranium through the use of fast breeder reactors, but this would involve totally unacceptable proliferation risks. In fast breeder reactors, the fuel rods consist of highly enriched uranium. Around the core, is an envelope of natural uranium. The flux of fast neutrons from the core is sufficient to convert a part of the U-238 in the envelope into Pu-239, a fissionable isotope of plutonium.

Fast breeder reactors are prohibitively dangerous from the standpoint of nuclear proliferation because both the highly enriched uranium from the fuel rods and the Pu-239 from the envelope are directly weapons-usable. It would be impossible, from the standpoint of equity, to maintain that some nations have the right to use fast breeder reactors, while others do not. If all nations used fast breeder reactors, the number of nuclear weapons states would increase drastically.

It is interesting to review the way in which Israel, South Africa, Pakistan, India and North Korea[5] obtained their nuclear weapons, since in all these cases the weapons were constructed under the guise of "atoms for peace", a phrase that future generations may someday regard as being tragically self-contradictory.

Israel began producing nuclear weapons in the late 1960's (with the help of a "peaceful" nuclear reactor provided by France, and with the tacit approval of the United States) and the country is now believed to possess 100-150 of them, including neutron bombs. Israel's policy is one of visibly possessing nuclear weapons while denying their existence.

South Africa, with the help of Israel and France, also weaponized its civil nuclear program, and it tested nuclear weapons in the Indian Ocean in 1979. In 1991 however, South Africa destroyed its nuclear weapons and signed the NPT.

India produced what it described as a "peaceful nuclear explosion" in 1974. By 1989 Indian scientists were making efforts to purify the lithium-6 isotope, a key component of the much more powerful thermonuclear bombs. In 1998, India conducted underground tests of nuclear weapons, and is now believed to have roughly 60 warheads, constructed from Pu-239 produced in "peaceful" reactors.

Pakistan's efforts to obtain nuclear weapons were spurred by India's 1974 "peaceful nuclear explosion". As early as 1970, the laboratory of Dr. Abdul Qadeer Khan, (a metallurgist who was to become Pakistan's leading nuclear bomb maker) had been able to obtain from a Dutch firm the high-speed ultracentrifuges needed for uranium enrichment. With unlimited financial support and freedom from auditing requirements, Dr. Khan purchased restricted items needed for nuclear weapon construction from companies in Europe and the United States. In the process, Dr. Khan became an extremely wealthy man. With additional help from China, Pakistan was ready to test five nuclear weapons in 1998. The Indian and Pakistani nuclear bomb tests, conducted in rapid succession, presented the

[4] Craig, J.R., Vaugn, D.J. and Skinner, B.J., *Resources of the Earth: Origin, Use and Environmental Impact, Third Edition*, page 210.

[5] Israel, India and Pakistan have refused to sign the Nuclear Non-Proliferation Treaty, and North Korea, after signing the NPT, withdrew from it in 2003.

world with the danger that these devastating weapons would be used in the conflict over Kashmir. Indeed, Pakistan announced that if a war broke out using conventional weapons, Pakistan's nuclear weapons would be used "at an early stage".

In Pakistan, Dr. A.Q. Khan became a great national hero. He was presented as the person who had saved Pakistan from attack by India by creating Pakistan's own nuclear weapons. In a Washington Post article[6] Pervez Hoodbhoy wrote: "Nuclear nationalism was the order of the day as governments vigorously promoted the bomb as the symbol of Pakistan's high scientific achievement and self-respect..." Similar manifestations of nuclear nationalism could also be seen in India after India's 1998 bomb tests.

Early in 2004, it was revealed that Dr. Khan had for years been selling nuclear secrets and equipment to Libya, Iran and North Korea, and that he had contacts with Al-Qaeda. However, observers considered that it was unlikely that Khan would be tried, since a trial might implicate Pakistan's army as well as two of its former prime ministers.

Recent assassination attempts directed at Pakistan's President, Pervez Musharraf, emphasize the precariousness of Pakistan's government. There a danger that it may be overthrown, and that the revolutionists would give Pakistan's nuclear weapons to a subnational organization. This type of danger is a general one associated with nuclear proliferation. As more and more countries obtain nuclear weapons, it becomes increasingly likely that one of them will undergo a revolution, during the course of which nuclear weapons will fall into the hands of criminals or terrorists.

If nuclear reactors become the standard means for electricity generation as the result of a future energy crisis, the number of nations possessing nuclear weapons might ultimately be as high as 40. If this should happen, then over a long period of time the chance that one or another of these nations would undergo a revolution during which the weapons would fall into the hands of a subnational group would gradually grow into a certainty.

There is also a possibility that poorly-guarded fissionable material could fall into the hands of subnational groups, who would then succeed in constructing their own nuclear weapons. Given a critical mass of highly-enriched uranium, a terrorist group, or an organized criminal (Mafia) group, could easily construct a crude gun-type nuclear explosive device. Pu-239 is more difficult to use since it is highly radioactive, but the physicist Frank Barnaby believes that a subnational group could nevertheless construct a crude nuclear bomb (of the Nagasaki type) from this material.

We must remember the remark of U.N. Secretary General Kofi Annan after the 9/11/2001 attacks on the World Trade Center. He said, "*This time* it was not a nuclear explosion". The meaning of his remark is clear: If the world does not take strong steps to eliminate fissionable materials and nuclear weapons, it will only be a matter of time before they will be used in terrorist attacks on major cities, or by organized criminals for the purpose of extortion. Neither terrorists nor organized criminals can be deterred by the threat of nuclear retaliation, since they have no territory against which such retaliation could be directed. They blend invisibly into the general population. Nor can a "missile defense system" prevent criminals or terrorists from using nuclear weapons, since the weapons can

[6] 1 February, 2004

be brought into a port in any one of the hundreds of thousands of containers that enter on ships each year, a number far too large to be checked exhaustively.

Finally we must remember that if the number of nations possessing nuclear weapons becomes very large, there will be a greatly increased chance that these weapons will be used in conflicts between nations, either by accident or through irresponsible political decisions.

On November 3, 2003, Mohamed ElBaradei, Director General of the International Atomic Energy Agency, made a speech to the United Nations in which he called for "limiting the processing of weapons-usable material (separated plutonium and high enriched uranium) in civilian nuclear programs - as well as the production of new material through reprocessing and enrichment - by agreeing to restrict these operations to facilities exclusively under international control." It is almost incredible, considering the dangers of nuclear proliferation and nuclear terrorism, that such restrictions were not imposed long ago.

From the facts that we have been reviewing, we can conclude that if nuclear power generation becomes widespread during a future energy crisis, and if equally widespread proliferation of nuclear weapons is to be avoided, the powers and budget of the IAEA will have to be greatly increased. All enrichment of uranium and reprocessing of fuel rods throughout the world will have to be placed be under direct international control, as has been emphasized by Mohamed ElBaradei. Because this will need to be done with fairness, such regulations will have to hold both in countries that at present have nuclear weapons and in countries that do not. It has been proposed that there should be an international fuel rod bank, to supply new fuel rods and reprocess spent ones. In addition to this excellent proposal, one might also consider a system where all power generation reactors and all research reactors would be staffed by the IAEA.

Nuclear reactors used for "peaceful" purposes unfortunately also generate fissionable isotopes of not only of plutonium, but also of neptunium and americium. Thus all nuclear reactors must be regarded as ambiguous in function, and all must be put under strict international control. One must ask whether globally widespread use of nuclear energy is worth the danger that it entails.

Let us now examine the question of whether nuclear power generation would appreciably help to prevent global warming. The fraction of nuclear power in the present energy generation spectrum is at present approximately 1/16. Nuclear energy is used primarily for electricity generation. Thus increasing the nuclear fraction would not affect the consumption of fossil fuels used directly in industry, transportation, in commerce, and in the residential sector. Coal is still a very inexpensive fuel, and an increase in nuclear power generation would do little to prevent it from being burned. Thus besides being prohibitively dangerous, and besides being unsustainable in the long run (because of finite stocks of uranium and thorium), the large-scale use of nuclear power cannot be considered to be a solution to the problem of anthropogenic climate change.

Optimists point to the possibility of using fusion of light elements, such as hydrogen, to generate power. However, although this can be done on a very small scale (and at great expense) in laboratory experiments, the practical generation of energy by means of thermonuclear reactions remains a mirage rather than a realistic prospect on which planners can rely. The reason for this is the enormous temperature required to produce thermonuclear reactions. This temperature is comparable to that existing in the interior of the sun, and it is sufficient to melt any ordinary container. Elaborate "magnetic bottles" have been constructed to contain thermonuclear reactions, and these have been used in successful very small scale experiments. However, despite 50 years of heavily-financed research, there has been absolutely no success in producing thermonuclear energy on a large scale, or at anything remotely approaching commercially competitive prices.

8.7 Cancer threat from radioactive leaks at Hanford USA

On August 9, 1945, a nuclear bomb was dropped on the Japanese city of Nagasaki. Within a radius of one mile, destruction was total. People were vaporized so that the only shadows on concrete pavements were left to show where they had been. Many people outside the radius of total destruction were trapped in their collapsed houses, and were burned alive by the fire that followed. By the end of 1945, an estimated 80,000 men, women, young children, babies and old people had died as a result of the bombing. As the years passed more people continued to die from radiation sickness.

Plutonium for the bomb that destroyed Nagasaki had been made at an enormous nuclear reactor station located at Hanford in the state of Washington. During the Cold War, the reactors at Hanford produced enough weapons-usable plutonium for 60,000 nuclear weapons. The continued existence of plutonium and highly-enriched uranium-235 in the stockpiles of nuclear weapons states hangs like a dark cloud over the future of humanity. A full scale thermonuclear war would be the ultimate ecological catastrophe, threatening to make the world permanently uninhabitable.

Besides playing a large role in the tragedy of Nagasaki, the reactor complex at Hanford has damaged the health of many thousands of Americans. The prospects for the future are even worse. Many millions of gallons of radioactive waste are held in Hanford's aging storage tanks, the majority of which have exceeded their planned lifetimes. The following quotations are taken from a Wikipedia article on Hanford, especially the section devoted to ecological concerns:

"A huge volume of water from the Columbia River was required to dissipate the heat produced by Hanford's nuclear reactors. From 1944 to 1971, pump systems drew cooling water from the river and, after treating this water for use by the reactors, returned it to the river. Before being released back into the river, the used water was held in large tanks known as retention basins for up to six hours. Longer-lived isotopes were not affected by this retention, and several tetrabecquerels entered the river every day. These releases were kept secret by the federal government. Radiation was later measured downstream as far west as the Washington and Oregon coasts."

"The plutonium separation process also resulted in the release of radioactive isotopes into the air, which were carried by the wind throughout southeastern Washington and into parts of Idaho, Montana, Oregon and British Colombia. Downwinders were exposed to radionuclide's, particularly iodine-131... These radionuclide's filtered into the food chain via contaminated fields where dairy cows grazed; hazardous fallout was ingested by communities who consumed the radioactive food and drank the milk. Most of these airborne releases were a part of Hanford's routine operations, while a few of the larger releases occurred in isolated incidents."

"In response to an article in the Spokane Spokesman Review in September 1985, the Department of Energy announced its intent to declassify environmental records and in February, 1986 released to the public 19,000 pages of previously unavailable historical documents about Hanford's operations. The Washington State Department of Health collaborated with the citizen-led Hanford Health Information Network (HHIN) to publicize data about the health effects of Hanford's operations. HHIN reports concluded that residents who lived downwind from Hanford or who used the Columbia River downstream were exposed to elevated doses of radiation that placed them at increased risk for various cancers and other diseases."

"The most significant challenge at Hanford is stabilizing the 53 million U.S. Gallons (204,000 m^3) of high-level radioactive waste stored in 177 underground tanks. About a third of these tanks have leaked waste into the soil and groundwater. As of 2008, most of the liquid waste has been transferred to more secure double-shelled tanks; however, 2.8 million U.S. Gallons (10,600 m^3) of liquid waste, together with 27 million U.S. gallons (100,000 m^3) of salt cake and sludge, remains in the single-shelled tanks.That waste was originally scheduled to be removed by 2018. The revised deadline is 2040. Nearby aquifers contain an estimated 270 billion U.S. Gallons (1 billion m^3) of contaminated groundwater as a result of the leaks. As of 2008, 1 million U.S. Gallons (4,000 m^3) of highly radioactive waste is traveling through the groundwater toward the Columbia River."

The documents made public in 1986 revealed that radiation was intentionally and secretly released by the plant and that people living near to it acted as unknowing guinea pigs in experiments testing radiation dangers. Thousands of people who live in the vicinity of the Hanford Site have suffered an array of health problems including thyroid cancers, autoimmune diseases and reproductive disorders that they feel are the direct result of these releases and experiments.

In thinking about the dangers posed by leakage of radioactive waste, we should remember that many of the dangerous radioisotopes involved have half-lives of hundreds of thousands of years. Thus, it is not sufficient to seal them into containers that will last for a century or even a millennium. We must find containers that will last for a hundred thousand years or more, longer than any human structure has ever lasted. This logic has lead Finland to deposit its radioactive waste in a complex of underground tunnels carved out of solid rock. But looking ahead for a hundred thousand years involves other problems: If humans survive for that long, what language will they speak? Certainly not the languages of today. How can we warn them that the complex of tunnels containing radioactive waste is a death trap? The reader is urged to see a film exploring these problems, "Into Eternity", by the young Danish film-maker Michael Madsen.

We have already gone a long way towards turning our beautiful planet earth into a nuclear wasteland. In the future, let us be more careful, as guardians of a precious heritage, the natural world and the lives of all future generations.

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Chapter 9

WATER AND DISEASE

9.1 WHO statement on warerborne disease

- **In 2017, 71% of the global population (5.3 billion people) used a safely managed drinking-water service - that is, one located on premises, available when needed, and free from contamination.**
- **90% of the global population (6.8 billion people) used at least a basic service. A basic service is an improved drinking-water source within a round trip of 30 minutes to collect water.**
- **785 million people lack even a basic drinking-water service, including 144 million people who are dependent on surface water.**
- **Globally, at least 2 billion people use a drinking water source contaminated with faeces.**
- **Contaminated water can transmit diseases such diarrhoea, cholera, dysentery, typhoid, and polio. Contaminated drinking water is estimated to cause 485 000 diarrheal deaths each year.**
- **By 2025, half of the world's population will be living in water-stressed areas.**
- **In least developed countries, 22% of health care facilities have no water service, 21% no sanitation service, and 22% no waste management service.**

9.2 Discovering the connection between cholera and sanitation

Cholera is a serious gastrointestinal disease caused by drinking water contaminated with cholera bacilli. If untreated, the death rate can be as high as 60%. Although in most developed countries, cholera is no longer a threat, it remains prevalent in many less-developed regions.

Wikipedia states that "Since it became widespread in the 19th century, cholera has killed tens of millions of people. In Russia alone, between 1847 and 1851, more than one million people perished of the disease. It killed 150,000 Americans during the second pandemic. Between 1900 and 1920, perhaps eight million people died of cholera in India.[Cholera became the first reportable disease in the United States due to the significant effects it had on health. John Snow, in England, was the first to identify the importance of contaminated water as its cause in 1854. Cholera is now no longer considered a pressing health threat in Europe and North America due to filtering and chlorination of water supplies, but still heavily affects populations in developing countries..."

Dr. John Snow and the Soho pumphandle

Dr. John Snow (1813-1858) made several important contributions to medicine. He was a leader in the development of anesthesia, and medical hygiene, and because if his work on the Soho cholera epidemic, he is considered to be one of the fathers of modern epidemiology. His work led to changes in public health practices throughout the world.

Born into a poor family in York, Snow exhibited an early aptitude for mathematics and science. At the age of only 14, he was apprenticed to a physician, and had the opportunity to observe the victims of a cholera epidemic. Snow later graduated from the University of London, and was admitted to the Royal College of Physicians in 1850.

Snow was a pioneer of anesthesiology, calculating the optimal dosages for the use of both chloroform and ether. He used these anesthetics in his practice of obstetrics. This created opposition from the Church of England, since it was believed the women were "meant to suffer in childbirth". However, in 1853 Queen Victoria asked Snow to administer chloroform during the birth of her eighth child. She repeated the request for her next birth, three years later.

John Snow lived before the establishment of the germ theory of disease by Louis Pasteur, Robert Koch and others. At the time when Snow lived, it was believed that diseases were caused by "miasma" or "bad air". Even before the Soho cholera epidemic, Snow's observations on the relationship between disease and sanitation had caused him to be skeptical of the "bad air" theory. In 1849 he published an essay entitled *On the Mode of Communication of Cholera*. However, it was the Soho cholera epidemic of 1854 that provided him with the hard evidence that he needed.

Describing his actions in the Soho epidemic, Snow later wrote in a letter to the editor of the Medical Times and Gazette, "On proceeding to the spot, I found that nearly all the deaths had taken place within a short distance of the [Broad Street] pump. There were only ten deaths in houses situated decidedly nearer to another street-pump. In five of these cases the families of the deceased persons informed me that they always sent to the pump in Broad Street, as they preferred the water to that of the pumps which were nearer. In three other cases, the deceased were children who went to school near the pump in Broad Street...

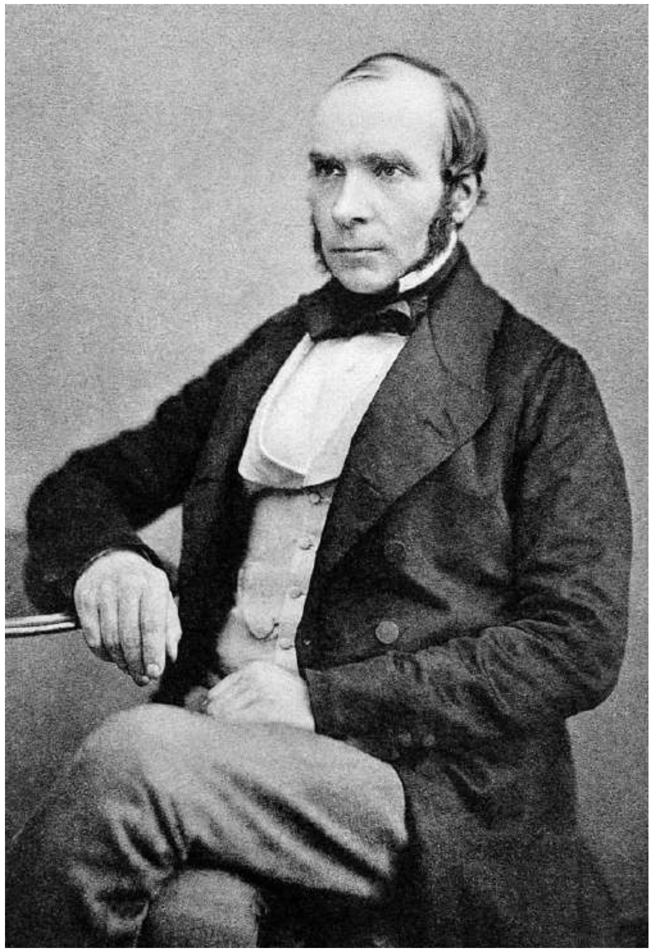

Figure 9.1: **John Snow in 1852.**

"With regard to the deaths occurring in the locality belonging to the pump, there were 61 instances in which I was informed that the deceased persons used to drink the pump water from Broad Street, either constantly or occasionally...

"The result of the inquiry, then, is, that there has been no particular outbreak or prevalence of cholera in this part of London except among the persons who were in the habit of drinking the water of the above-mentioned pump well.

"I had an interview with the Board of Guardians of St James's parish, on the evening of the 7th inst [7 September], and represented the above circumstances to them. In consequence of what I said, the handle of the pump was removed on the following day."

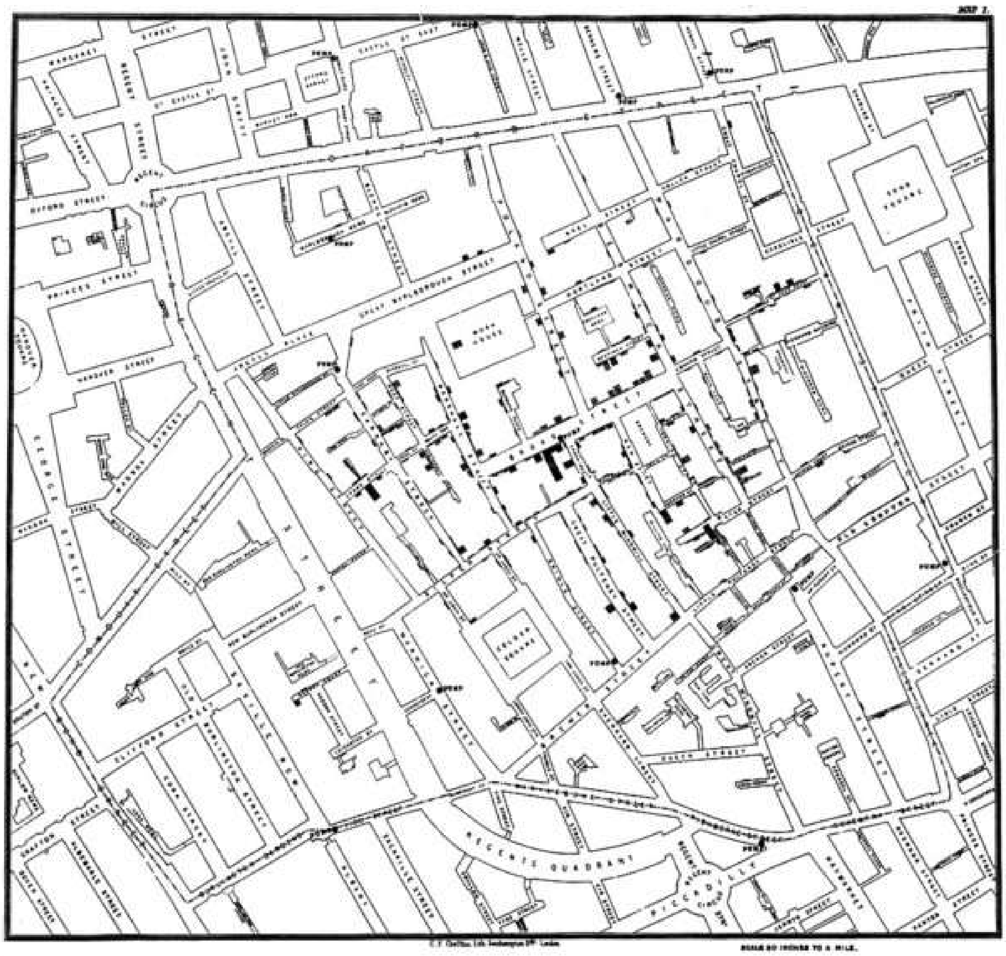

Figure 9.2: **John Snow's map, showing that all of the cases of cholera in the Soho outbreak occurred near to a particular pump.**

Figure 9.3: **The John Snow memorial and public house.**

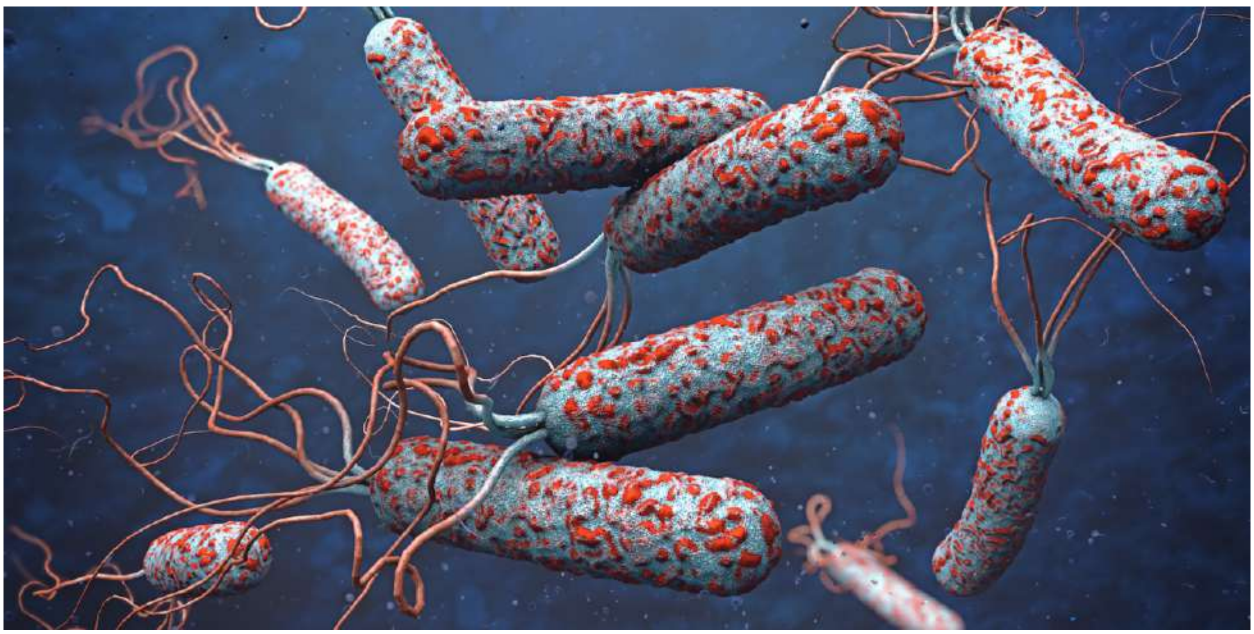

Figure 9.4: **Cholera bacteria. In 1883, the German physician, Robert Koch, isolated the bacterium Vibrio cholerae, finally discovering the cause of the disease. He determined that cholera is spread through unsanitary water or food supply sources, supporting Snow's theory from 20 years earlier. However, John Snow did not live to see his theories vindicated. At the time of Koch's discoveries, he had died of a stroke in 1858, at the age of only 45.**

9.3 The history of cholera

Cholera has been known since ancient times. The disease is thought to have originated in India, and it is still very prevalent there.

During the last 200 years, there have been seven cholera pandemics. The list given below is from Wikipedia:

1. The first cholera pandemic (1817-1824), also known as the first Asiatic cholera pandemic or Asiatic cholera, began near the city of Calcutta and spread throughout South and Southeast Asia to the Middle East, eastern Africa and the Mediterranean coast.

2. The second cholera pandemic (1826-1837), also known as the Asiatic cholera pandemic, was a cholera pandemic that reached from India across western Asia to Europe, Great Britain, and the Americas, as well as east to China and Japan.

3. The third cholera pandemic (1846-1860) was the third major outbreak of cholera originating in India in the nineteenth century that reached far beyond its borders, which researchers at UCLA believe may have started as early as 1837 and lasted until 1863. In Russia, more than one million people died of cholera. In 1853-1854, the epidemic in London claimed over 10,000 lives, and there were 23,000 deaths for all of Great Britain. This pandemic was considered to have the highest fatalities of the 19th-century epidemics.

4. The fourth cholera pandemic of the 19th century, 1863-1875, began in the Ganges Delta of the Bengal region and traveled with Muslim pilgrims to Mecca. In its first year, the epidemic claimed 30,000 of 90,000 pilgrims. Cholera spread throughout the Middle East and was carried to Russia, Europe, Africa and North America, in each case spreading via travelers from port cities and along inland waterways.

5. The fifth cholera pandemic (1881-1896) was the fifth major international outbreak of cholera in the 19th century. It spread throughout Asia and Africa, and reached parts of France, Germany, Russia, and South America. It claimed 200,000 lives in Russia between 1893 and 1894; and 90,000 in Japan between 1887 and 1889. The 1892 outbreak in Hamburg, Germany was the biggest European outbreak; about 8,600 people died in that city. Although many residents held the city government responsible for the virulence of the epidemic (leading to cholera riots in 1893), it continued with practices largely unchanged. This was the last serious European cholera outbreak of the century.

6. The sixth cholera pandemic (1899-1923) was a major outbreak of cholera beginning in India, where it killed more than 800,000 people, and spreading to the Middle East, North Africa, Eastern Europe and Russia.

7. The 1961-1975 cholera pandemic (also known as the seventh cholera pandemic) was the seventh major outbreak of cholera and occurred principally from the years 1961 to 1975; the strain involved persists to the present. This pandemic, based on the strain called El Tor, started in Indonesia in 1961 and spread to Bangladesh by 1963. Then it went to India in 1964, followed by the Soviet Union by 1966. In July 1970, there was an outbreak in Odessa and in 1972 there were reports of outbreaks in Baku, but the Soviet Union suppressed this information. It reached Italy in 1973 from North Africa. Japan and the South Pacific saw a few outbreaks by the late 1970s. In 1971, the number of cases reported worldwide was 155,000. In 1991, it reached 570,000. The spread of the disease was helped by modern transportation and mass migrations. Mortality rates, however, dropped markedly as governments began modern curative and preventive measures. The usual mortality rate of 50% dropped to 10% by the 1980s and less than 3% by the 1990s

9.4 River blindness

Onchocerciasis, which is also known as "river blindness", is a disease caused by infection with a parasitic worm. The disease is carried by a black fly of the Simulium type, which lives near to rivers in Africa.

There is no vaccine against river blindness, so campaigns to prevent the disease rely on spraying to eliminate the flies that are its carriers. Also, treatment of infected populations helps to eliminate the disease.

River blindness causes much economic damage by making populations abandon the fertile banks of rivers and lakes. About 21 million people were infected with this parasite in 2017 and of these about 1.2 million had vision loss.

9.5 Schistosomiasis

Schistosomiasis is a disease caused by parasitic flatworms called schistosomes. Part of the life-cycle of these parasitic worms is spent in snails that live in bodies of water, and the disease is spread when people step into water in which the snails are living.

The symptoms of schistosomiasis are abdominal pain, diarrhea, bloody stool, and blood in the urine, and the disease may lead to liver damage, kidney failure, infertility and bladder cancer.

In 2010, approximately 238 million people were infected with schistosomiasis, 85 percent of whom live in Africa.

9.6 Typhoid fever

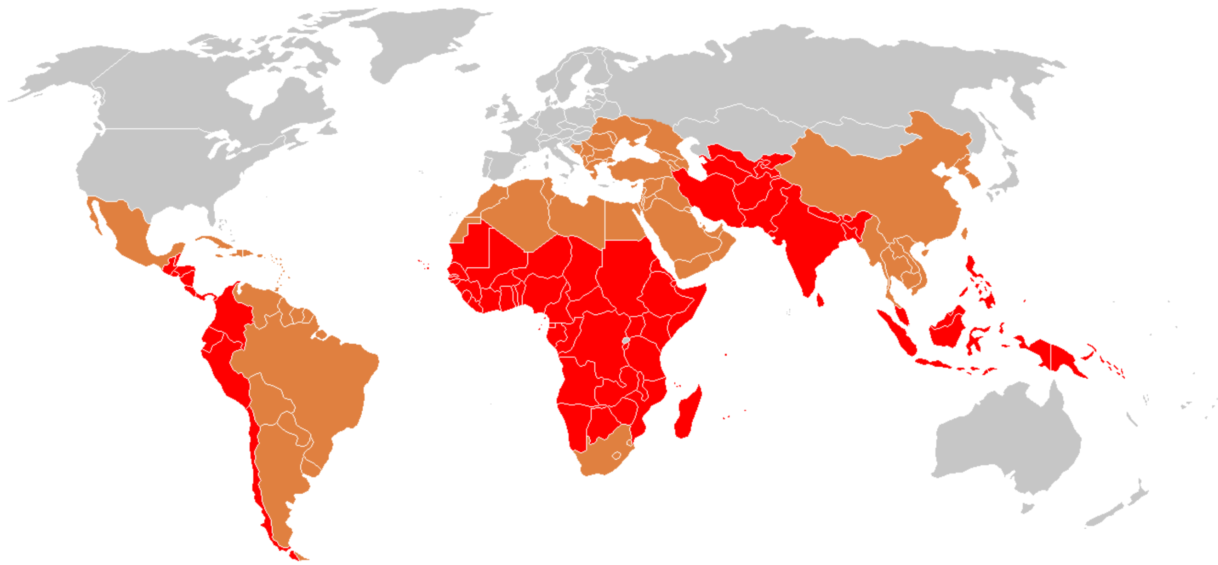

Figure 9.5: **Incidence of typhoid fever today. Red indicates very high incidence, and brown means moderate incidence. In the remainder of the world, the incidence is sporadic.**

9.7 Bacillary and amoebic dysentery

Bacillary dysentery is caused by the bacillus shigella. and it is often transmitted through drinking unclean water that has been contaminated with sewage. Amoebic dysentery is similarly transmitted, but in this case the infecting organism is the amoeba Entamoeba histolytica.

Victims of dysentery experience repeated loose bowel movements containing blood, and they usually suffer from severe dehydration. If not treated properly, amoebic dysentery may lie dormant and recur many years later.

Dysentery of the shigella type currently results in approximately 165 million cases every year, and 1.1 million deaths. Almost all the cases occur in the developing parts of the world.

9.8 Tehran's water supply in 1945

In 1945, when I lived in Tehran with my parents and brother, the population of Tehran was about 600,000. (Today it has grown into a modern mega-metropolis of more than 12 million!) The city was built on a sloping plane that led up to the base of the Elburz mountains. The altitude of Tehran was about 3,000 feet, but the northern part was of course higher than the southern part because of the slope of the plane. Today, Tehran extends right up to the base of the mountains which start at about 6,000 feet.

When we lived there water from the mountains flowed through Tehran in the jubes or ditches beside the streets, becoming progressively dirtier as it flowed southward. Therefore the nice part of the city was the north part, because the water was cleaner. Those who could afford it drank water that came to the city from mountain springs in an ancient system of underground tunnels called "qnats". Water from the qnats was carried around the Tehran in horse-drawn tank carts. The driver of such a cart had with him a stack of buckets, and as he drove he called out (for example) "Ab Ali! Ab Ali!" The word "Ab" is farsi for water, and "Ali" the name of a particular qnat.

Before being distributed, the water from the qnats was very pure and safe. However, the distribution system had its faults: When he found a customer, the water cart driver would place his buckets in a row on the sidewalk and fill them with water. When the transaction was complete, he would stack the buckets, one inside the other, and then drive on. Thus, because of the stacking, the contamination from the sidewalk would find its way from the bottom of one bucket into the bucket below it.

Our house was surrounded by a high wall, with gates at the front and rear. When one looked out of the window of the pink-marble-floored upstairs bathroom, it was possible to look down to the street outside the wall and to see a family of beggars who lived there both summer and winter. The wall was their only protection from the elements. They drank water directly from the ditch (in farsi called "jube"), into which filth from the street and sidewalk was swept. They made their own contribution to the filth, since they had no bathroom other than the wall.

It seemed incredible to me that they did not all die quickly from such a life. In fact, the rate of infant mortality was extremely high. Those few children who did survive, however, had acquired immunity to most of the forms of dysentery. It was also painful to contrast their poverty with our wealth, and I strongly wished to help them. However, poverty was everywhere in Iran at that time.

Today Iran is a modern nation and the city of Tehran has a safe modern water system and a modern sanitary system as well. However, in some developing countries, conditions similar to those just described for Tehran in 1945 persist today.

Suggestions for further reading

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Chapter 10

WATER WARS

10.1 Historical conflicts related to water

Here are some excerpts from a very large list given on the following website:

http://www.worldwater.org/conflict/list/

- **3000 BC, Ancient Sumerian legend recounts the deeds of the deity Ea, who punished humanity for its sins by inflicting the Earth with a six-day storm. The Sumerian myth parallels the Biblical account of Noah and the deluge, although some details differ.**

- **2500 BC, Lagash-Umma border dispute, Mesopotamia: The dispute over the Gu'edena (edge of paradise) region begins. Urlama, King of Lagash from 2450 to 2400 BC, diverts water from this region to boundary canals, drying up boundary ditches to deprive Umma of water. His son Il cuts off the water supply to Girsu, a city in Umma.**

- **1720-1684 BC, Tigris River dammed, Mesopotamia: A grandson of Hammurabi, Abish or Abi-Eshuh, dams the Tigris to prevent the retreat of rebels led by Iluma-Ilum, who declares the independence of Babylon. This failed attempt marks the decline of the Sumerians who had reached their apex under Hammurabi.**

- **circa 1300 BC, Kishon River flooded in defeat of Sisera: The Old Testament gives an account of the defeat of Sisera and his 'nine hundred chariots of iron' by the unmounted army of Barak on the fabled Plains of Esdraelon. God sends heavy rainfall in the mountains, and the Kishon River overflows the plain and immobilizes or destroys Sisera's technologically superior forces ("...the earth trembled, and the heavens dropped, and the clouds also dropped water," Judges 5:4; "...The river of Kishon swept them away, that ancient river, the river Kishon," Judges 5:21).**

- **720-705 BC, Assyrian king destroys Armenian irrigation network: After a successful campaign against the Halidians of Armenia, Sargon II of Assyria destroys their intricate irrigation network and floods their land.**

- **612 BC, Khosr River diverted by Babylonians, Assyria: A coalition of Egyptian, Median (Persian), and Babylonian forces attacks and destroys Nineveh, the capital of Assyria. Nebuchadnezzar's father, Nabopolassar, leads the Babylonians. The converging armies divert the Khosr River to create a flood, which allows them to elevate their siege engines on rafts.**

- **590-600 BC, Athens poisons enemies' water: Athenian legislator Solon reportedly has roots of helleborus thrown into a small river or aqueduct leading from the Pleistrus River to Cirrha during a siege of this city. The enemy forces become violently ill and are defeated as a result. Some accounts have Solon building a dam across the Plesitus River cutting off the city's water supply. Such practices are widespread.**

- **355-323 BC, Alexander tears down Persian dams, Babylon: Returning from the razing of Persepolis, Alexander proceeds to India. After the Indian campaigns, he heads back to Babylon via the Persian Gulf and the Tigris, where he tears down defensive weirs that the Persians had constructed along the river. The Greek historian Arrian describes Alexander's disdain for the Persians' attempt to block navigation, which he saw as "unbecoming to men who are victorious in battle."**

- **204 BC, Wei River dams in China are breached in 204 BC: An intentional rupturing of the Wei River dams leads to the victory of Han Dynasty forces.**

- **51 BC, Caesar attacks water supplies during siege of Uxellodunum, Roman Empire: Caesar attacks water supplies during siege of Uxellodunum by undermining one of the local springs and placing attackers near the other. Shortage of water leads to the surrender of the Gauls.**

- **537, Goths cut Roman aqueducts, Roman Empire: In the 6th century AD, as the Roman Empire begins to decline, the Goths besiege Rome and cut almost all of the aqueducts leading into the city. In 537 AD this siege is successful. The only aqueduct that continues to function is the Aqua Virgo, which runs almost entirely underground.**

- **1187, Saladin cuts off Crusaders' water, Principality of Galilee: Saladin is able to defeat the Crusaders at the Horns of Hattin in 1187 by denying them access to water. In some reports, Saladin fills all the wells along the way with sand and destroys the villages of the Maronite Christians who would supply the Christian army with water.**

- **1503, Florence plan to cut Pisa's water, Republic of Florence: Leonardo da Vinci and Machiavelli plan to divert Arno River away from Pisa during conflict between Pisa and Florence (Italy).**

- **1642, 300,000 deaths when Yellow River dikes are breached. China: In 1642, in a battle between the incoming Manchu and the forces of the Ming dynasty, Yellow River (China) dikes are breached by both sides, creating a catastrophe for Kaifeng in which 300,000 of its 378,000 citizens die.**

- **1777, British attack New York's water: British and Hessians attack the water system of New York. "...the enemy wantonly destroyed the New York water works" during the War for Independence.**

- **1860-1865, US Civil War soldiers poison wells: General William T. Sherman's memoirs contain an account of Confederate soldiers poisoning ponds by dumping the carcasses of dead animals into them. Other accounts suggest this tactic was used by both sides.**

- **1898, France and Britain battle over Nile, Mahdist State, Northern Africa: Military conflict nearly ensues between Britain and France in 1898 when a French expedition attempts to gain control of the headwaters of the White Nile. While the parties ultimately negotiate a settlement of the dispute, the incident is since characterized as having "dramatized Egypt's vulnerable dependence on the Nile, and fixed the attitude of Egyptian policy-makers ever since."**

- **1907-1913, Los Angeles aqueduct bombed: he Los Angeles Valley aqueduct/pipeline suffers repeated bombings in an effort to prevent diversions of water from the Owens Valley to Los Angeles.**

- **1938, China floods Yellow River to defend from Japan: Chiang Kai-shek orders the destruction of flood-control dikes of the Huayuankou, Henan section of the Huang He (Yellow) River, in order to flood areas threatened by the Japanese army. West of Kaifeng, dikes are destroyed with dynamite, spilling water across the flat plain. Even though the flood destroys part of the invading army and mires its equipment in mud, Wuhan, the headquarters of the Nationalist government is taken by the Japanese in October. Floodwaters cover an area variously estimated as between 3,000 and 50,000 square kilometers, and kill Chinese estimated in numbers between "tens of thousands" and "one million."**

- **1941-1943, WWII damages Soviet's hydroelectric dams: World War II inflicts enormous harm to hydroelectricity systems in the Soviet Union. Over two-thirds of the hydroelectric power stations are lost.**

- **1947-1960s, Indus divided between India and Pakistan: Partition leaves Indus basin divided between India and Pakistan; disputes over irrigation water ensue, during which India stems flow of water into irrigation canals in Pakistan. Indus Waters Agreement reached in 1960 after 12 years of World Bank-led negotiations.**

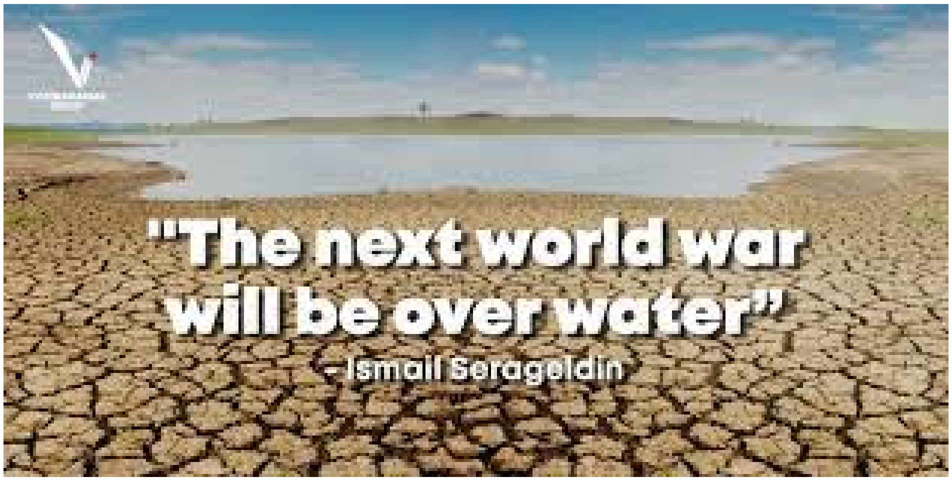
- **1951, Israel and Syria fight over Yarmouk River: ordan makes public its plans to irrigate the Jordan Valley by tapping the Yarmouk River; Israel responds by commencing drainage of the Huleh swamps located in the demilitarized zone between Israel and Syria; border skirmishes ensue between Israel and Syria.**

- **1962-1967, Brazil and Paraguay clash over Paraná River: Negotiations between Brazil and Paraguay over the development of the Paraná River are interrupted by a unilateral show of military force by Brazil in 1962, which invades the area and claims control over the Guadalajara Falls site. Military forces are withdrawn in 1967 following an agreement for a joint commission to examine development in the region.**

- **1975, Iraq, Syria mobilize troops over drought tensions: As upstream dams are filled during a low-flow year on the Euphrates, Iraqis claim that flow reaching its territory is "intolerable" and asks the Arab League to intervene. Syrians claim they are receiving less than half the river's normal flow and pull out of an Arab League technical committee formed to mediate the conflict. In May Syria closes its airspace to Iraqi flights and both Syrian and Iraq reportedly transfer troops to their mutual border. Saudi Arabia successfully mediates the conflict.**

- **1978 onwards, Egypt threatens Ethiopia over Nile plans: Long standing tensions over the Nile, especially the Blue Nile, originate in Ethiopia. Ethiopia's proposed construction of dams on the headwaters of the Blue Nile leads Egypt to repeatedly declare the vital importance of water. "The only matter that could take Egypt to war again is water' (Anwar Sadat, 1979). "The next war in our region will be over the waters of the Nile, not politics" (Boutros Boutros-Ghali, 1988).**

- **1990-1991, Attacks on energy systems in Iraq leaves cities without water: During the Gulf War, targeted attacks on transformers and turbines at water treatment plants leave whole cities, such as Basra, without water or wastewater treatment. And due to embargos, parts needed to fix the plants are not available. It is estimated that at least 25% of water treatment plants in Iraq do not have backup power supply and are inoperable after electrical grids are damaged. Human Rights Watch 1991**



- **1991-2001, US sanctions against Iraq target water systems: United States deliberately pursues policy of destroying Iraq's water systems through sanctions and withholding contracts.**


WATER
WARS


water wars


WATER WARS
WHEN DROUGHT, FLOOD AND GREED COLLIDE
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10.2 Conflicts over water in the Middle East

Here are some quotations from an article by Sagatom Saha entitled *How climate change could exacerbate conflicts in the Middle East*[1]

"Global warming will do the Middle East no favors. Evidence abounds it will be the region that climate change will hit hardest. Summer temperatures across the region are expected to increase more than twice the global average. Prolonged heat waves, desertification, and droughts will make parts of the Middle East and North Africa uninhabitable. Where Middle Easterners will still be able to live, climate change may fuel violent competition over diminishing resources. Even though some degree of warming is inevitable, governments in the region and their international partners have done little to integrate climate change to their strategies to mitigate instability and conflict. Instead, they should brace themselves for a Middle East in which warming intensifies unrest, weakens state capacity, and provokes resource conflicts.

"For an early example of warming's damaging power, look no further than Syria. Climate change caused the generational drought that preceded the ongoing civil war there. That drought drove rural farmers into urban centers like Damascus and Aleppo, priming the populace for concentrated, large-scale political unrest. From 2002 to 2010, the country's total urban population increased by 50 percent. While climate change certainly did not compel Bashar Al-Assad to brutally crack down on his own people, it did prompt a confrontation that might not have occurred. Climate-induced economic despair and migration worked to reinforce other salient conflict drivers including Assad's "privatization" efforts and concentration of power that exaggerated inequality and severed the dictator's connection to rural, recently migrated communities. As climate change causes rapid temperature increases, food shortages, and economic pain elsewhere, more Middle Eastern countries might tip over into bloodshed.

"Climate-induced water shortages will be another source of conflict. When the Islamic State controlled large swathes of territory across Iraq and Syria, it wrested control of dams that provided drinking water, electricity, and irrigation to millions along the Tigris and Euphrates rivers. Ensuing clashes with Kurdish and Iraqi forces left Shiite holy cities like Karbala and Najaf without water. More than 23 million live in the river basin, and experts predict that, because of global warming, the Tigris and Euphrates will "disappear this century," making conflict over what remains even more tempting if contested political control returns to the Fertile Crescent.

"Further, climate change will likely make Middle Eastern governments less

[1] https://www.atlanticcouncil.org/blogs/menasource/how-climate-change-could-exacerbate-conflict-in-the-middle-east/

capable of handling unrest. First, more frequent weather events will surely put a drag on resource delivery and create new emergency relief needs. In the Middle East where foreign assistance is often critical, donors may have to work double time to continue to fund stabilization and governance projects while also providing more humanitarian disaster aid.

"Second, oil producers will have fewer resources as oil receipts contract amid the inevitable global clean energy transition that will accompany climate action. Take the fact that worsening climate change is already driving a global transition toward clean energy. In November 2018, even while pursuing close cooperation with the Organization of Petroleum Exporting Countries (OPEC), Russian President Vladimir Putin openly declared that "$70 suits us completely," referring to an ideal oil price for his country. Unlike his Middle Eastern partners, Putin seems to acknowledge that OPEC oil will face market competition from renewables and US shale if it reaches too high a price.

"In countries where the social contract rests upon limited political freedom in exchange for subsidies and extravagant public works, there will be less money to go around, and it cannot be expected to go as far. Such is the case in Algeria, where street demonstrations have forced the country's ailing leader, Abdelaziz Bouteflika, to step down. Protesters' grievances are, in part, tied to the oil, which funded social benefits that buoyed youth employment until prices crashed.

"While countries like Saudi Arabia have the financial capacity to likely weather the storm, worry should be aimed squarely at unstable oil producers like Iraq and Libya, which require extraordinarily oil prices to fund budgets. It is true that oil is a valuable, concentrated resource that factions compete for in the region, but it may be a necessary source of reconstruction funding once conflict abates. In the best case, foreign assistance continues to come from western governments like the United States that still rely on the global flow of oil to some degree. In the worst case, donor governments abdicate their support as the mass deployment of wind turbines, solar panels, and electric vehicles become more feasible and affordable. The consequences could be locking in the fragility of the region's current conflict zones: Even though Libyan militias fight to control oil infrastructure now, it is hard to imagine the country funding its own reconstruction in the future unless oil returns to a higher price.

"Climate change might also have the Middle East's governments warier of their neighbors. Resource scarcity within a country can provoke nationwide unrest, but competition over transboundary resources can elevate even higher to bellicose levels. Knowing that water will become scarcer, it is instructive to understand how Middle Eastern neighbors are already handling disputes over water needed for irrigation, drinking, and hydropower production.

"The Nile River Basin provides one worrying example. Since 2011, Ethiopia has been constructing its Grand Renaissance Dam in a bid to become a regional

electricity exporter. However, the dam will slash downstream flow to Egypt by 25 percent. Cairo alleges that the dam will interrupt water supplies to its nearly 100 million people. While Ethiopia and Egypt are currently in negotiations, Egyptian officials have been caught considering military action over the dispute as recently as 2013. The current Egyptian president Abdel Fattah el-Sisi has openly declared the dam "a matter of life and death," highlighting its continued importance. Climate change, which threatens to disrupt the Nile's flows, stands to make an already tense situation worse.

"Admittedly, direct conflict between Middle Eastern countries has become rarer, but proxy wars are common, featuring in nearly all the region's civil wars. Water has already featured in at least one of them: Historically, Damascus has leveraged support for the Kurdistan Workers Party (PKK), a group loathed by Istanbul, to force Turkey to share Euphrates waters to Syria. Nearly every country in the Middle East from Morocco to Iran share water resources with a neighbor, and some have little freshwater of their own. What has played out between Egypt and Sudan and between Turkey and Syria could become a frequent feature of Middle Eastern politics as water becomes even more scarce."

Suggestions for further reading

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Chapter 11

WATER AND BIOLOGICAL SPECIFICITY

11.1 Hydrogen bonds in water

In the water molecule, there is a small positive excess charge, $+\delta$, on each of the hydrogens, and a small negative excess charge, -2δ, on the oxygen. Hydrogen bonds in water and ice are formed by Coulomb attractions between these positive and negative charges. In the figure shown below, the hydrogen bonds are represented by dotted lines. The insolubility of nonpolar molecules is due to the fact that they break up the hydrogen bonds in water, and it thus costs energy to incorporate them into water.

Polar molecules, on the other hand, can fit into the hydrogen bonding system of water by forming their own hydrogen bonds with water molecules, and thus they are water-soluble.

Soaps and detergents have a polar end, attached to a long nonpolar tail. They allow groups of nonpolar molecules to become water-soluble by forming a layer with the polar ends pointing outward to the water, while the long non-polar ends point inwards.

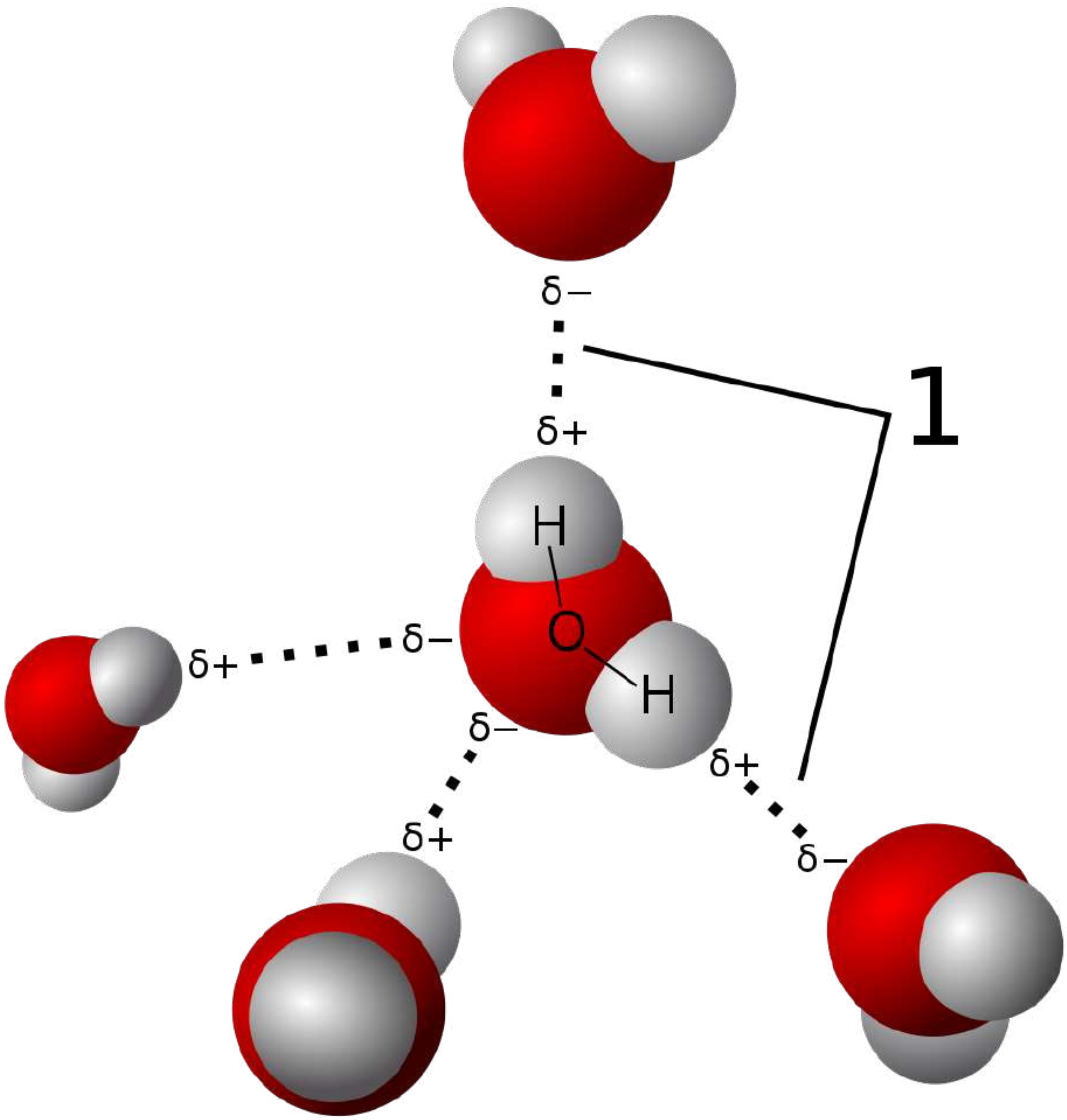

Figure 11.1: **In the water molecule, there is a small positive excess charge, $+\delta$, on each of the hydrogens, and a small negative excess charge, -2δ, on the oxygen. Hydrogen bonds in water and ice are formed by Coulomb attractions between these positive and negative charges. In this figure, the hydrogen bonds are represented by dotted lines. The insolubility of nonpolar molecules is due to the fact that they break up the hydrogen bonds in water, and it thus costs energy to incorporate them into water.**

11.2 Water and the folding of proteins

When I worked at the Imperial College of Science and Technology in London, during the 1960's, I was a member of the Royal Institution of Great Britain, where Michael Faraday was once the director, and where Faraday gave lectures on science that were attended by Queen Victoria's husband, Prince Albert and his sons.

The tradition of polished and entertaining lectures initiated by Faraday is continued today. I vividly remember attending a lecture on the structure of the protein, lysozyme.

Lysozyme was the first antibacterial agent discovered by Alexander Fleming. He was disappointed to find that the pathogenic bacteria against which it is effective are not associated with very serious diseases. In fact, these diseases are not serious because the human body produces the enzyme lysozyme. We have it, for example, in our nasal mucus.

But back to the Royal Institution lecture on the structure of lysozyme, which had been determined by the use of X-ray crystallography. As in Faraday's day, the lecture was given with much style. The lecturer was the person responsible for solving the structure, David Chilton Phillips (1925-1999), who was later made a Life Peer, Baron Phillips of Ellesmere.

Hanging from the ceiling of the lecture room was a long chain model of the amino acid sequence of the lysozyme macro-molecule, before folding. D.C. Phillips explained all the difficulties of obtaining good crystals and performing the X-ray diffraction experiments. Then he said "Finally, after much work, and a little prayer, we obtained a structure", and he gazed upward, as if to heaven. Then dramatically, a model of the folded protein was lowered downward towards us from its previously unseen position at the top of the room.

Phillips flipped a switch, and we saw on the linear model, the positions of the hydrophilic amino acids and the hydrophobic ones, indicated respectively by green and red lights, Then flipping another switch, he showed us their positions on the folded molecule. The hydrophilic amino acids were all on the outside, while the hydrophobic ones were on the inside. The surrounding water had determined the way in which the protein had folded (its tertiary structure) as well as its enzymatic activity. We could see clearly the active site of lysozyme, its "mouth", where it bit into the cell walls of bacteria.

The case of lysozyme is surely not an isolated one. It seems logical to generalize from this case, and to think that the tertiary structure and enzymatic activity of all water-soluble proteins is determined by the interaction of hydrophilic and hydrophobic amino acids with the surrounding water.

11.3 The second law of thermodynamics

The second law of thermodynamics was discovered by Nicolas Leonard Sadi Carnot (1796-1832) and elaborated by Rudolf Clausius (1822-1888) and William Thomson (later Lord Kelvin, 1824-1907). Carnot came from a family of distinguished French politicians and military men, but instead of following a political career, he studied engineering. In 1824, his only scientific publication appeared - a book with the title *Reflections on the Motive Power of Fire*. Although it was ignored for the first few years after its publication, this single book was enough to secure Carnot a place in history as the founder of the science of thermodynamics. In his book, Carnot introduced a scientific definition of work which we still use today - "weight lifted through a height"; in other words, force times distance.

At the time when Carnot was writing, much attention was being given to improving the efficiency of steam engines. Although James Watt's steam engines were far more efficient than previous models, they still could only convert between 5 % and 7 % of the heat energy of their fuels into useful work. Carnot tried to calculate the theoretical maximum of the efficiency of steam engines, and he was able to show that an engine operating between the temperatures T_1 and T_2 could at most attain

$$\text{maximum efficiency} = \frac{T_1 - T_2}{T_1} \tag{11.1}$$

Here T_1 is the temperature of the input steam, and T_2 is the temperature of the cooling water. Both these temperatures are absolute temperatures, i.e., temperatures proportional to the volume of a given quantity of gas at constant pressure.

Carnot died of cholera at the age of 36. Fifteen years after his death, the concept of absolute temperature was further clarified by Lord Kelvin (1824-1907), who also helped to bring Carnot's work to the attention of the scientific community.

Building on the work of Carnot, the German theoretical physicist Rudolph Clausius was able to deduce an extremely general law. He discovered that the ratio of the heat content of a closed system to its absolute temperature always increases in any process. He called this ratio the entropy of the system. In the notation of modern thermodynamics, the change in entropy dS when a small amount of heat dq is transferred to a system is given by

$$dS = \frac{dq}{dT} \tag{11.2}$$

Let us imagine a closed system consisting of two parts, one at temperature T_1, and the other part at a lower temperature T_2. If a small amount of heat dq flows from the warmer part to the cooler one, the small resulting change in entropy of the total system will be

$$dS = \frac{dq}{T_1} - \frac{dq}{T_2} > 0 \tag{11.3}$$

According to Clausius, since heat never flows spontaneously from a colder object to a warmer one, the entropy of a closed system always increases; that is to say, dS is always positive. As heat continues to flow from the warmer part of the system to the cooler part, the system's energy becomes less and less available for doing work. Finally, when the two parts have reached the same temperature, no work can be obtained. When the parts differed in temperature, a heat engine could in principle be run between them, making use of the temperature difference; but when the two parts have reached the same temperature, this possibility no longer exists. The law stating that the entropy of a closed system always increases is called the second law of thermodynamics.

11.4 Statistical mechanics

Besides his monumental contributions to electromagnetic theory, the English physicist James Clerk Maxwell (1831-1879) also helped to lay the foundations of statistical mechanics. In this enterprise, he was joined by the Austrian physicist Ludwig Boltzmann (1844-1906) and by an American, Josiah Willard Gibbs, whom we will discuss later.

As a young student, Boltzmann read Maxwell's paper on the velocity distributions of molecules in a gas, and he spent the remainder of his life developing these Maxwell's initiative into the science of statistical mechanics. Boltzmann was able to derive the following equation hold for the particles in a perfect (non-interacting) gas:

$$\frac{n_i}{N} = \frac{e^{-\epsilon_i/kT}}{\sum_i e^{-\epsilon_i/kT}} \tag{11.4}$$

Here n_i represents the number of particles in a state with energy ϵ_l, while N is the total number of particles. T is the absolute temperature, and k, which is called *Boltzmann's constant*, has a dimension such that the dimension of kT is energy.

Like Maxwell, Boltzmann also interpreted an increase in entropy as an increase in disorder; and like Maxwell he was a firm believer in atomism at a time when this belief was by no means universal. For example, Ostwald and Mach, both important figure in German science at that time, refused to believe in the existence of atoms, in spite of the fact that Dalton's atomic ideas had proved to be so useful in chemistry. Towards the end of his life, Boltzmann suffered from periods of severe depression, perhaps because of attacks on his scientific work by Ostwald and others. In 1906, while on vacation near Trieste, he committed suicide - ironically, just a year before the French physicist J.B. Perrin produced irrefutable evidence of the existence of atoms.

When a system is in thermodynamic equilibrium, its entropy has reached a maximum; but if it is not in equilibrium, its entropy has a lower value. For example, let us think of the case which was studied by Clausius when he introduced the concept of entropy: Clausius imagined an isolated system, divided into two parts, one of which has a temperature T_i, and the other a lower temperature, T_2. When heat is transferred from the hot part to the cold part, the entropy of the system increases; and when equilibrium is finally established at some uniform intermediate temperature, the entropy has reached a maximum. The difference in entropy between the initial state of Clausius' system and its final state is a measure of how far away from thermodynamic equilibrium it was initially.

Figure 11.2: **The English physicist James Clerk Maxwell (1931-1879). Together with Ludwig Boltzmann, he was one of the founders of statistical mechanics. Maxwell took the first step in a paper on the velocity distributions of molecules in a gas.**

Figure 11.3: **The Austrian physicist Ludwig Boltzmann (1844-1906), the co-founder of statistical mechanics. As a young student, Boltzmann read Maxwell's paper on velocity distributions, and he spent the remainder of his life developing these ideas into the science of statistical mechanics.**

11.5 Gibbs free energy

The American physicist Josiah Willard Gibbs (1839-1903) made many contributions to thermodynamics and statistical mechanics. In 1863, Gibbs received from Yale the first Ph.D. in engineering granted in America, and after a period of further study in France and Germany, he became a professor of mathematical physics at Yale in 1871, a position which he held as long as he lived. During the period between 1876 and 1878, he published a series of papers in the *Transactions of the Connecticut Academy of Sciences*. In these papers, about 400 pages in all, Gibbs applied thermodynamics to chemical reactions. (The editors of the *Transactions of the Connecticut Academy of Sciences* did not really understand Gibbs' work, but, as they said later, "We knew Gibbs, and we took his papers on faith".)

Because the journal was an obscure one, and because Gibbs' work was so highly mathematical, it remained almost unknown to European scientists for a long period. However, in 1892 Gibbs' papers were translated into German by Ostwald, and in 1899 they were translated into French by Le Chatelier; and then the magnitude of Gibbs' contribution was finally recognized. One of his most important innovations was the definition of a quantity which we now call "Gibbs free energy". This quantity allows one to determine whether or not a chemical reaction will take place spontaneously.

Chemical reactions usually take place at constant pressure and constant temperature. If a reaction produces a gas as one of its products, the gas must push against the pressure of the earth's atmosphere to make a place for itself. In order to take into account the work done against external pressure in energy relationships, the German physiologist and physicist Hermann von Helmholtz introduced a quantity (which we now call heat content or enthalpy) defined by

$$H = U + PV \tag{11.5}$$

where U is the internal energy of a system, P is the pressure, and V is the system's volume.

Gibbs went one step further than Helmholtz, and defined a quantity which would also take into account the fact that when a chemical reaction takes place, heat is exchanged with the surroundings. Gibbs defined his free energy by the relation

$$G = U + PV - TS \tag{11.6}$$

or

$$G = H - TS \tag{11.7}$$

where S is the entropy of a system, H is its enthalpy, and T is its temperature.

Gibbs' reason for introducing the quantity G is as follows: The second law of thermodynamics states that in any spontaneous process, the entropy of the universe increases. Gibbs invented a simple model of the universe, consisting of the system (which might, for example, be a beaker within which a chemical reaction takes place) in contact with a large thermal reservoir at constant temperature. The thermal reservoir could, for example, be a water bath so large that whatever happens in the chemical reaction, the temperature of the bath will remain essentially unaltered. In Gibbs' simplified model, the entropy change

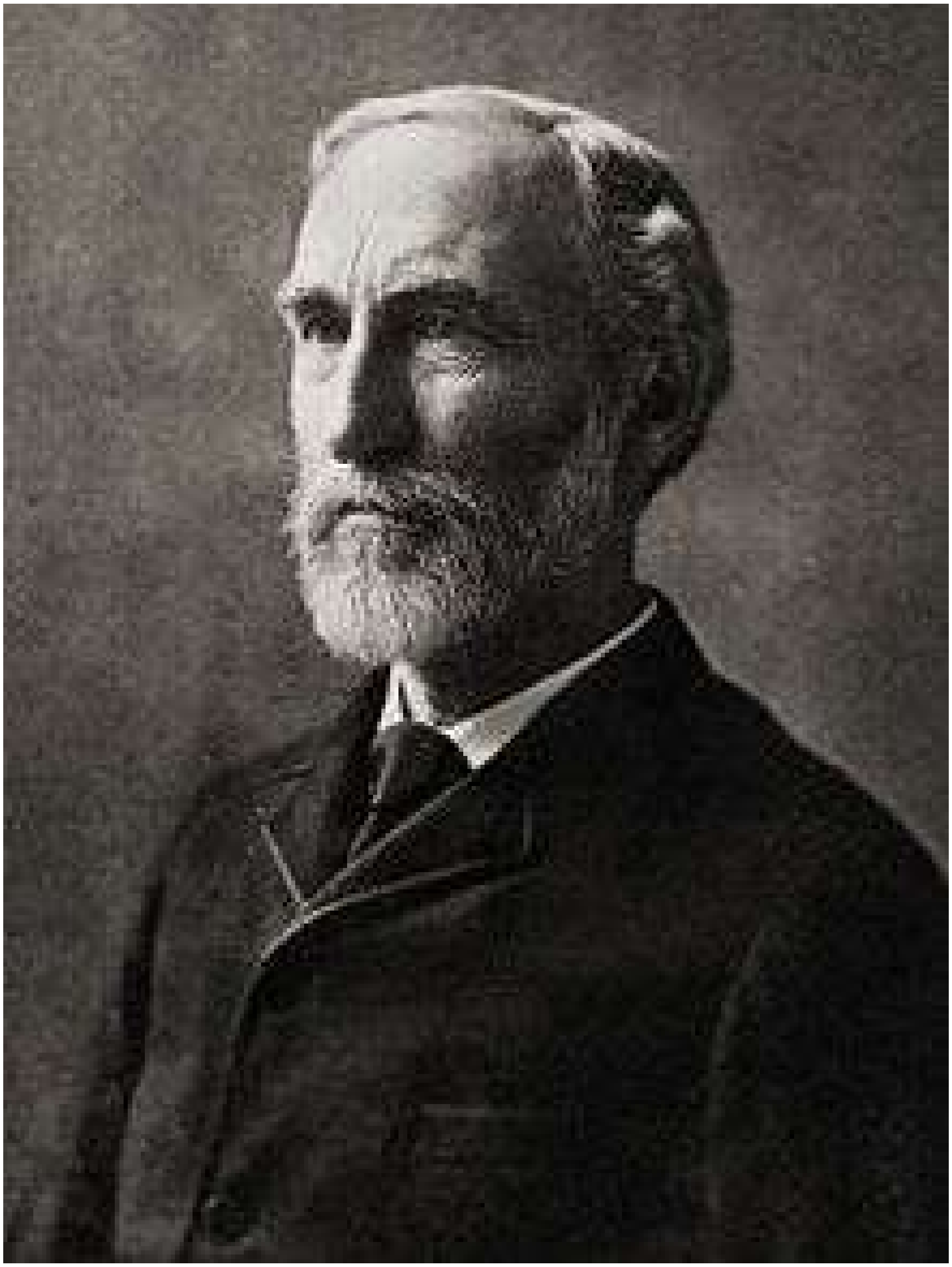

Figure 11.4: **Josiah Willard Gibbs (1839-1903). He found a way to apply thermodynamics to chemistry.**

of the universe produced by the chemical reaction can be split into two components:

$$\Delta S_{universe} = \Delta S_{system} + \Delta S_{bath} \tag{11.8}$$

Now suppose that the reaction is endothermic (i.e. it absorbs heat). Then the reaction beaker will absorb an amount of heat ΔH_{system} from the bath, and the entropy change of the bath will be

$$\Delta S_{bath} = -\frac{\Delta H_{system}}{T} \tag{11.9}$$

Combining (13.8) and (13-9) with the condition requiring the entropy of the universe to increase, Gibbs obtained the relationship

$$\Delta S_{universe} = \Delta S_{system} - \frac{\Delta H_{system}}{T} > 0 \tag{11.10}$$

The same relationship also holds for exothermic reactions, where heat is transferred in the opposite direction. Combining equations (13.38) and (13.35) yields

$$\Delta G_{system} = -T\Delta S_{universe} < 0 \tag{11.11}$$

Thus, the Gibbs free energy for a system must decrease in any spontaneous chemical reaction or process which takes place at constant temperature and pressure.

Measured values of the "Gibbs free energy of formation", ΔG_f°, are available for many molecules. To construct tables of these values, the change in Gibbs free energy is measured when the molecules are formed from their constituent elements. The most stable states of the elements at room temperature and atmospheric pressure are taken as zero points. For example, water in the gas phase has a Gibbs free energy of formation

$$\Delta G_f^\circ(H_2O) = -228.59\ \frac{\text{kJ}}{\text{mol}} \tag{11.12}$$

This means that when the reaction

$$H_2(g) + \frac{1}{2}O_2(g) \to H_2O(g) \tag{11.13}$$

takes place under standard conditions, there is a change in Gibbs free energy of $\Delta G^\circ =$ –228.59 kJ/mol [1]. The elements hydrogen and oxygen in their most stable states at room temperature and atmospheric pressure are taken as the zero points for Gibbs free energy of formation. Since ΔG° is negative for the reaction shown in this equation, the reaction is spontaneous. In general, the change in Gibbs free energy in a chemical reaction is given by

$$\Delta G^\circ = \sum_{products} \Delta G_f^\circ - \sum_{reactants} \Delta G_f^\circ \tag{11.14}$$

where ΔG_f° denotes the Gibbs free energy of formation.

[1] The superscript ° means "under standard conditions", while kJ is an abbreviation for joule$\times 10^3$.

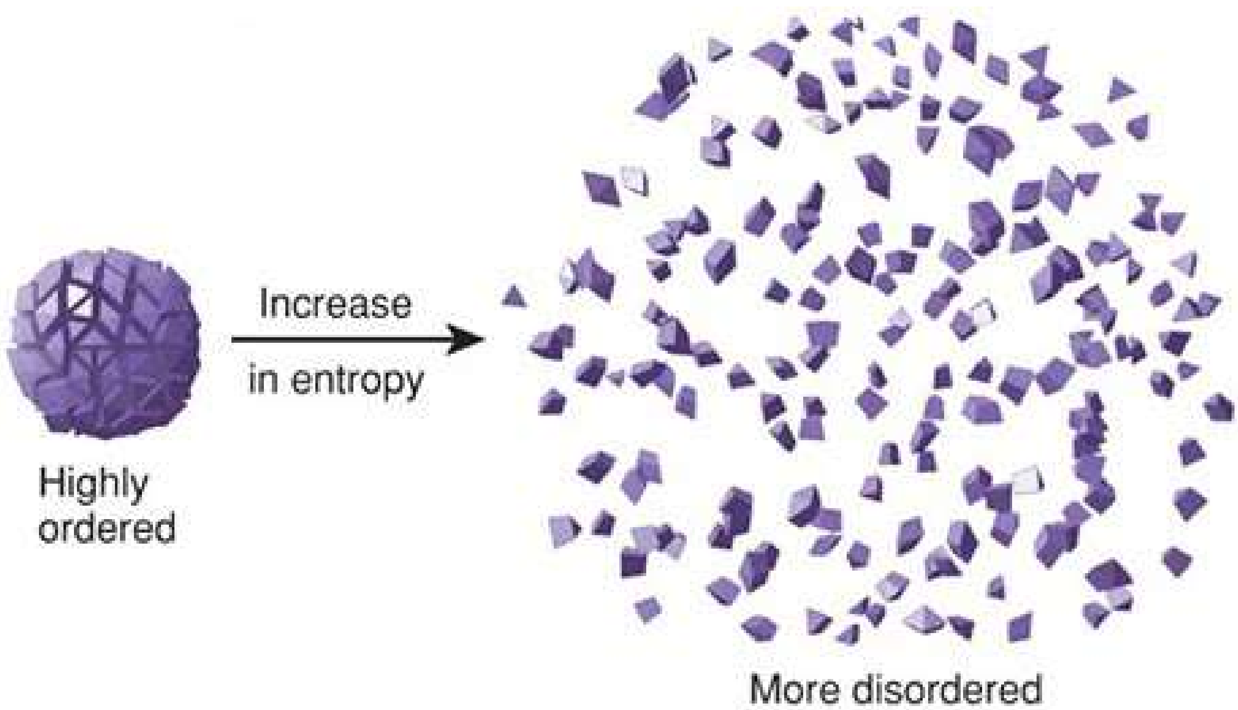

Figure 11.5: **According to the second law of thermodynamics, the entropy of the universe constantly increases. Increase of entropy corresponds to increase of disorder, and also to in- crease of statistical probability. Living organisms on the earth are able to achieve a high degree of order and highly improbable structures because the earth is not a closed system. It constantly receives free energy (i.e. energy capable of doing work) from the sun, and this free energy can be thought of as carrying thermodynamic information, or "negative entropy".**

As a second example, we can consider the reaction in which glucose is burned:

$$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(g) \qquad \Delta G^\circ = -2870 \, \frac{\text{kJ}}{\text{mol}} \tag{11.15}$$

The oxidation of glucose illustrates the importance of enzymes and specific coupling mechanisms in biology. A lump of glucose can sit for years on a laboratory table, fully exposed to the air. Nothing will happen. Even though the oxidation of glucose is a spontaneous process - even though the change in Gibbs free energy produced by the reaction would be negative - even though the state of the universe after the reaction would be much more probable than the initial state, the reaction does not take place, or at least we would have to wait an enormously long time to see the glucose oxidized, because the reaction pathway is blocked by potential barriers.

11.6 Svante Arrhenius

Svante Augustus Arrhenius was born in Wik Castle, Sweden in 1859, the son of Svante Gustav and Carolina Thunberg Arrhenius. He was a child prodigy, who without encouragement from his parents, taught himself to read at the age of 3. As a very young child, he also became an arithmetical prodigy by watching his father add numbers in his account books.

Arrhenius started research at the University of Uppsala, but he was dissatisfied with the instruction in physics and chemistry. In 1881 he moved to the Swedish Academy of Sciences in Stockholm. There he produced a Ph.D. dissertation which focused on conductivity of electrolytes. The dissertation was so contrary to the chemical ideas of the time that it was accepted only grudgingly by the committee judging it, and Ahrrenius was only granted a 4th class degree. Nevertheless, the 56 propositions put forward in the dissertation are universally accepted today, almost entirely without modification, and they won Ahrrenius the 1903 Nobel Prize in Chemistry.

Michael Faraday (1791-1867) had previously shown that charged particles, which he named "ions", could carry an electrical current through a solution. Ahrrenius developed Faraday's concept of ions by demonstrating that when salts are dissolved in water, ions are present even without an electrical current. He also defined acids to be substances which produce solutions in which H^+ ions predominate, while in bases, when dissolved, produce solutions in which OH^- ions predominate.

In chemical reaction theory, Ahrrenius introduced the idea of an activation energy, E_a, which can be thought of as the height of an energy barrier which must be surmounted in order for the reaction to take place. Thus most chemical reactions become more probable when the temperature T is raised, since the rapid motion of the reactants at higher temperatures can supply the energy needed to overcome the reaction barrier E_a. Ahrrenius connected the concept of activation energy with the statistical mechanics of Ludwig

Figure 11.6: **Svante Arrhenius (1859-1927) was one of the main founders of physical chemistry and a pioneer of climate science. He was related to climate activist Greta Thunberg, and Greta's father is named after him.**

Boltzmann (1844-1906) by means of his famous equation:

$$K = A\ e^{-E_a/RT}$$

In the Ahrrenius equation, K is the reaction rate, A is a constant proportional to the frequency of reactant collisions with the proper orientation, T is the absolute temperature, and R is the constant that appears in the equation of state of a perfect gas, $PV = nRT$.

11.7 The role of water in biological specificity

Below is a paper based on a lecture that I gave at a conference in Sorrento, Italy. The lecture discusses the role of water in biological specificity. In 1984 a paper based on the lecture was published in the International Journal of Quantum Chemistry. The paper has also been translated into Czech, and published in the Journal of the Czech Academy of Sciences.

To understand the role of water in biological specificity, let us imagine two opposite electrical charges in an aqueous environment. If the water were not there, the attraction between the two opposite charges would fall off as the square of the distance between them. However, there are water molecules between the two opposite charges, and to find the effective forces, we must consider the Gibbs free energy, $G = U + PV - TS$, of the total system, including the water. When two opposite electrical charges are in an aqueous environment, the water molecules separating them become aligned so that their electric dipole moments point in the direction of the electric field. This alignment lowers the entropy of the system and raises its Gibbs free energy. Thus an effective force is produced in a direction that will lower the Gibbs free energy by reducing the volume of polarized water. This force acts strongly over a much larger distance than a simply Coulomb force. Thus the two opposite charges, which might be excess charges on the active site of an enzyme and its substrate, or an antigen and an antibody, are drawn together by the thermodynamic force that seeks to minimize the number of polarized water molecules separating them.

This thermodynamic effective force explains how the important biological processes such as auto-assembly of structures. or enzymatic activity can function so efficiently. It is because the thermodynamic forces function strongly over a much longer range than Coulomb forces, and they draw the complementary charges on the enzyme and substrate molecules, or antigen-antibody molecules, together with efficiency over much longer distances than Coulomb attraction alone could achieve.

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A Model for Biological Specificity*

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Abstract

The phenomenon of biological specificity is described, and a history of discoveries related to the phenomenon is presented. Aspects of biological specificity described include the mechanism of the immune system, chemotherapy, enzyme-substrate specificity, neurotransmitters, autoassembly of viruses, autoassembly of subcellular organelles, differentiation, and cellular recognition. A model for biological specificity involving both steric and electrostatic complementarity is presented and the role of structured water and hydrophobic forces is also discussed.

During the coming week, the lectures at this meeting will deal with biological topics. Most of us here are quantum chemists or physicists—That is certainly what I am myself. If we wish to apply our methods to biological problems, we are faced with a dilemma: The difficulty is that both quantum chemistry and biology are subjects which require a whole lifetime to learn thoroughly, so that it is impossible for any single person to have a deep knowledge of both fields. So what are we to do? Almost the only possibility available to us is to collaborate with a biologist or a biochemist. In such a partnership, each person has to learn enough of the other's field so that they can talk together. I hope that this lecture will serve as a contribution to the effort which we as quantum chemists must make to learn some biology. We need to make this effort in order to have biologists as friends and collaborators, and in order to appreciate the remarkable things which are happening in their field.

In this lecture, I would like to review the history of discoveries and ideas related to biological specificity. I hope in this way to convince you that the phenomenon of specificity is extremely widespread and fundamental in the operation of biological systems. I hope to show that it is involved not only in the mechanism of the immune system, but also in the mechanism of chemotherapy, in enzyme-substrate specificity, in the mechanism of neurotransmitters, in the autoassembly of viruses, in the autoassembly of subcellular organelles, in differentiation and cellular recognition, in the senses of taste and smell, and in hormone-receptor specificity. Finally, I would like to present a model of biological specificity—a model which involves both steric and electrostatic complementarity; and I will try to discuss briefly the role of structured water and hydrophobic forces.

Let us begin by looking at the history of immunology and chemotherapy. The first important discovery in this field was made by Edward Jenner in the 18th

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century. It had been known for a long time that a person who had once been infected by smallpox and who had recovered was afterwards immune to the disease. In ancient China, a powder was made from dry crusts taken from cases of smallpox, and this powder was sniffed up the nose. The result was usually a mild case of smallpox, and the innoculated person was afterwards immune. The practice of innoculation against smallpox was brought to England in 1717 by Lady Mary Montagu, the wife of the Bristish Ambassador to Turkey. This method was like Russian roulette, because it sometimes produced a fatal case of the disease. However, in 1796, Edward Jenner demonstrated that it was possible to produce immunity to smallpox by innoculation with cowpox, a much milder disease.

The discovery of a safe method of vaccination against smallpox was greeted with enormous enthusiasm everywhere in Europe. The British Parliament voted Jenner a reward of £30,000, his birthday was celebrated as a holiday in Germany, and in Russia, the first child to be vaccinated was named Vaccinov and was educated at the expense of the state.

Jenner's discovery greatly influenced Louis Pasteur. He studied Jenner's papers with extreme care and he speculated continually about how a method of safe vaccination could be found for other diseases besides smallpox. Pasteur finally was able to develop vaccines for several diseases, including anthrax and rabies, and he established general methods for preparing vaccines. We would now explain Pasteur's methods by saying that when bacteria are grown under certain abnormal conditions, a few mutant bacteria are favored by the conditions of growth. The mutants multiply, and the normal bacteria disappear. The mutant bacteria are unable to cause a serious case of the disease, but they nevertheless have antigens on their surfaces which are able to provoke a response of the immune system.

The first real understanding of the mechanism of the immune system was due to the work of Paul Ehrlich and Ilya Mechnikov, and in 1908 they shared a Nobel Prize for this work. Paul Ehrlich can be said to be the discoverer of biological specificity. As a young medical student at the University of Strasbourg, he was fortunate to work under the distinguished chemist Heinrich von Waldeyer, who took a great interest in Ehrlich. Stimulated by Waldeyer, Ehrlich began to do experiments in which he prepared thin slices of various tissues for microscopic examination by staining them with the newly discovered aniline dyes. During the last half of the 19th century, there was a great deal of interest in histological staining. It was during this period that Walther Flemming in Germany discovered chromosomes by staining them with special dyes, and Christian Gram in Denmark showed that bacteria can be classified into two types by staining methods. (We now call these two types "gram positive" and "gram negative"). During this same period, and while he was still a student, Paul Ehrlich made the important discovery that mammalian blood contains three different types of white cells which can be distinguished by staining.

Ehrlich's early work on staining made him famous, and it also gave him a set of theories which led him to his great discoveries in immunology and chemotherapy. According to Ehrlich's ideas, the color of the aniline dyes is due to the aniline ring. However, dyes used commercially must also adhere to fabrics, and this adherence, according to Ehrlich, is due to the specific structure of the side chains. If the pattern of atoms on a side chain is complementary to the pattern of atoms on the binding site, the dye will adhere, but otherwise not. Thus there is a "lock and key" mechanism, and for this reason dyes with specific side chains stain specific types of tissue.

In one of his experiments, Paul Ehrlich injected methylene blue into the ear of a living rabbit, and found that it stained only the nerve endings of the rabbit. Since the rabbit seemed to be unharmed by the treatment, the experiment suggested to Ehrlich that it might be possible to find antibacterial substances which could be safely injected into the bloodstream of a patient suffering from an infectious disease. Ehrlich hoped to find substances which would adhere selectively to the bacteria, while leaving the tissues of the patient untouched.

With the help of a large laboratory especially constructed for him in Frankfurt, the center of the German dye industry, Ehrlich began to screen thousands of modified dyes and other compounds. In this way he discovered trypan red, a chemical treatment for sleeping sickness, and arsphenamine, a drug which would cure syphilis. Ehrlich thus became the father of modern chemotherapy. His success pointed the way to Gerhard Domagk, who discovered the sulphonamide drugs in the 1930s, and to Fleming, Waksman, Dubos and others, who discovered the antibiotics.

Ehrlich believed that in the operation of the immune system, the body produces molecules which have a pattern of atoms complementary to patterns (antigens) on invading bacteria, and that these molecules (antibodies) in the blood stream kill the bacteria by adhering to them. Meanwhile, the Russian naturalist Ilya Mechnikov discovered another mechanism by which the immune system operates. While on vacation in Sicily, Mechnikov was studying the digestive process in starfish larvae. In order to do this, he introduced some particles of carmine into the larvae. The starfish larvae were completely transparent, and thus Mechnikov could look through his microscope and see what happened to the particles. He saw that they were enveloped and apparently digested by wandering amoebalike cells inside the starfish larvae. As he watched this process, it suddenly occurred to Mechnikov that our white cells might similarly envelop and digest bacteria, thus protecting us from infection. Describing this discovery, Mechnikov wrote in his diary: "I suddenly became a pathologist! Feeling that there was in this idea something of surpassing interest, I became so excited that I began striding up and down the room, and even went to the seashore to collect my thoughts."

Mechnikov later named the white cells "phagocytes" (which means "eating cells"). He was able to show experimentally that phagocytosis (i.e., the envelopment and digestion of bacteria by phagocytes) is an important mechanism in immunity. For a number of years, there were bitter arguments between those who thought that the immune system operates through phagocytosis, and those who thought that it operates through antibodies. Finally it was found that both mechanisms play a role. In phagocytosis, the bacterium will not be ingested by the phagocyte unless it is first studded with antibodies. Thus both Mechnikov and Ehrlich were proved to be right.

Early in the 20th century, important work in immunology was done by Karl Landsteiner, who won the 1930 Nobel Prize in medicine and physiology for his discovery of the human blood groups. His book, entitled *The Specificity of Serological Reactions,* is listed in the references [1]. In 1936, Landsteiner asked Linus Pauling (who was then visiting the Rockefeller Institute for Medical Research), to try to develop a theory which would account for antibody-antigen specificity in the operation of the immune system [2]. The result was a theory by Pauling, in which some features were correct, but others badly wrong. Pauling decided that "... The specific combining region of an antibody molecule is complementary in structure to a portion of the surface of the antigen, with the antigen-antibody bond resulting from the cooperation of weak forces (electronic van der Waals forces, electrostatic interaction of charged groups, and hydrogen bonding) between the complementary structures, over an area sufficiently large that the total binding energy can resist the disrupting influence of thermal agitation." This much of Pauling's 1940 theory is today considered to be correct. However, Pauling also made the hypothesis—and this is where he went wrong—that in the immune system, the antigen serves as a template for the construction of the antibody (in much the same way that a DNA strand serves as a template for the construction of the complementary strand). Once the lymphocytes have "learned" how to produce antibodies fitting a particular antigen, Pauling believed, they continue to produce them, and thus we become immune [3].

Pauling's reason for believing in a template theory of antibody formation was the enormous range of specificities which can be matched. The mammalian immune system can produce antibodies of roughly 10^7 different specificities. It seemed impossible to Pauling that so many different specificities could be genetically coded. However, subsequent research [4–6] has shown that the capability for producing this immense variety of antibodies is, in fact, genetically programmed. Each lymphocyte produces its own specific antibody molecule, and when a lymphocyte divides, the daughter cells continue to produce exactly the same antibody. Animals of a particular species, when challenged with a particular antigen, may be unable to produce an antibody against it, while animals of a slightly different genetic strain, when challenged with the same antigen, can readily produce the appropriate antibody.

Thus, Pauling's template theory of immunity had to be abandoned. It was replaced by the clonal theory of Niels Kai Jerne and Sir Frank MacFarlane Burnet. According to the clonal theory of immunity, which is the currently accepted theory, a few lymphocytes corresponding to each of the 10^7 different specificities are present in a nonimmune individual. When the individual becomes ill with an infection, antigens on the surfaces of the invading microorganisms bind to antibody molecules on the surfaces of just those lymphocytes which have the right specificity. This stimulates the selected lymphocytes to divide rapidly, and after a period of time, a population of lymphocytes capable of producing the correct antibody builds up. When this happens, the infected individual recovers. Even after recovery, a substantial population of that strain of lymphocyte remains, and if the individual is again invaded by the same type of microorganism, this population of lymphocytes can immediately produce the appropriate antibody. an individual with this capability is immune.

The clonal theory of immunity has an interesting consequence: Because of the fact that when a lymphocyte divides, the daughter cells produce exactly the same antibody as the parent, it follows that if one could culture lymphocytes, one could produce pure antibodies *in vitro*. However, if one tries to culture these cells in a direct way, they die after a few generations. In 1975, Georges Köhler and Cesar Milstein succeeded in culturing lymphocytes by fusing them with myeloma cancer cells. The resulting hybrid cell lines were immortal, and cultures from single cells could be grown indefinitely, producing pure "monoclonal" antibodies [6–15].

The monoclonal antibody technique of Köhler and Milstein allows one to separate mixtures of unknown composition into their components. This is done in the following way: A mouse is immunized with the mixture, and spleen cells from the mouse are fused with myeloma cells. The hybrid cells are spread out into several hundred small culture dishes, one cell to each dish. After a clone has grown from the single cell in each dish, the supernatants are reacted one at a time with the mixture. Each component of the mixture makes an insoluble product with a different supernatant, and thus the mixture is separated into its components.

The monoclonal antibody technique is an extremely powerful tool, which can be used in the purification of proteins, the characterization of viruses, the treatment of cancer, in genetic studies, and in many other applications.

Until now, we have been considering only immunology and chemotherapy as examples of biological specificity. However, specificity is a much more general and fundamental phenomenon in biology. For example, one can see the phenomenon in operation in the autoassembly of viruses and subcellular organelles. Fraenkel-Conrat [16] has shown that by changing the pH, it is possible to take a virus to pieces. When the original pH is restored, the pieces spontaneously reassemble themselves into a virus capable of producing an infection. A similar spontaneous assembly must also occur whenever a virus reproduces itself. After the constituent parts have been manufactured by the ribosomes of the host cell, they must come together spontaneously. This process is analogous to crystallization, but more complicated, since the virus contains molecules of several different kinds. How can the pieces "know" enough to fit themselves together? The answer must be that regions on each constituent molecule of a virus are complementary to regions on the neighboring molecule of the finished structure, so that they bind selectively to the right place, and perhaps are even attracted to the right place. The same kind of spontaneous assembly, analogous to crystallization, must occur in the autoassembly of subcellular organelles, such as chloroplasts and mitochondria.

Specificity is also important in the operation of the central nervous system. A number of different substances are released at synapses (for example, acetylcholine, noradrenalin, serotonin, and dopamine). These neurotransmitter substances can stimulate or inhibit the firing of the next neuron, each substance being specific to a particular type of receptor on the neighboring neuron [17–20].

Cell surface antigens are involved in differentiation during the development of an embryo. For example, the H-Y antigen (a pattern of atoms which is present on the plasma membrane of all male mammalian cells) is known to be a differentiation antigen. The H-Y antigen [21–30] has been shown to be present on the cell surfaces of male mammalian embryos at the eight-cell stage, and it has been shown to be involved in the development of the embryo into a male, long before testosterone is present in the embryo. If the H-Y antigen is absent, the embryo develops into a female. Interestingly, the H-Y antigen seems to play a similar role in birds, reptiles, and amphibians; but in birds, it occurs on the cells of the female, and in amphibians, sometimes on the cells of one sex, and sometimes the other. This irregularity is only superficial, however, since the H-Y antigen is invariably linked to the development of the heterogametic sex. In the case of mammals, the male is heterogametic; in the case of birds, the female is heterogametic; and in the case of amphibians, the heterogametic sex is variable, depending on the species.

Other areas of biology where specificity plays an important role include the senses of taste and smell [31, 32], enzyme-substrate interactions [33–35] and hormone-receptor interactions.

I would like to end this lecture by proposing a model for biological specificity. The model consists of three assertions: (1) The complementarity involved in biological specificity is, in general, both steric and electrostatic. (2) There is a matching of nonpolar regions. (3) The total system, including water molecules, tends to move in such a way that its Gibbs free energy, $G = E + PV - TS$, decreases.

The last point in the model has been called the "thermodynamic hypothesis" by Anfinsen [36], and he has shown that it holds in the folding of proteins. ("Hypothesis" is almost too modest a name for the rule that the Gibbs free energy of a system tends to decrease, since this rule is one of the main guiding principles of theoretical chemistry.) One can even define a "thermodynamic force," as has been done by Buckingham and McLachlan [37–40]. If the Gibbs free energy G is a function of N coordinates, $x_1, x_2, \ldots, x_N$ (which might represent nuclear coordinates), then the thermodynamic force corresponding to one of the coordinates is given by $\partial G/\partial x_i$. The direction of this force gives the direction in which the system tends to move, according to the thermodynamic hypothesis. However, one should remember that this is not the same kind of force which enters Newton's equations.

The first point in the model does not mention dispersion forces. This is not because dispersion forces are always negligibly small, but because it is hard to visualize complementarity with respect to dispersion forces. In cases where dispersion forces are important, it is steric complementarity which allows the two specific combining regions to come close enough to each other so that the dispersion forces are effective. Hydrogen bonds also go unmentioned in the first point of the model, but this is because they are included under the heading of electrostatic complementarity.

As Professor Tomasi has emphasized in his lecture, when two molecules approach each other but are not yet in contact, the classical electrostatic interaction between them is often the dominant term in the interaction energy [41]. Alberte and Bernard Pullman have also emphasized the importance of electrostatic interactions [42–45]. Thus, when we visualize the interaction between, for example, an enzyme and its substrate as they approach each other, we should visualize the interaction as being initially primarily electrostatic. Only after the approach has become very close (~1–2 Å), will other types of forces become important.

We must now ask what role the solvent water molecules will play. The large variety of ways in which a water molecule can form hydrogen bonds with its neighbors contributes to the entropy of water. When this freedom to form hydrogen bonds in many ways is restricted, the entropy is decreased. If we introduce a nonpolar molecule into water, the water molecules around it become more highly ordered and "icelike," the variety of ways in which they form hydrogen bonds is limited, and thus the entropy is decreased. This is the reason for the well-known insolubility of nonpolar molecules in water [49, 50]. The entropy term in the Gibbs free energy,

$$G = E + PV - TS, \tag{1}$$

favors configurations in which the contact of water with nonpolar molecules or groups is minimized. This hydrophobic effect has the consequence that in biological specificity, nonpolar regions of combining sites tend to come together in order to escape contact with water (point 2 of the model).

The entropy of water is also reduced when the water molecules are aligned by an electric field. Water has a high dielectric constant, which is due to the dipole moment formed by the positively charged hydrogens and the negatively charged oxygen lone pairs [46–62]. When two charges interact with each other in an aqueous medium, the intervening water molecules align themselves with their dipole moments pointing in such a way that the interaction energy of the two charges is reduced. Thus, at first sight, it would seem that the effect of the polarized water between two charges would be to very much reduce their attraction for each other. We should remember, however, that the Gibbs free energy of the system also contains an entropy term, and this term has the opposite effect. When water molecules are aligned in the electric field, their entropy is lowered. If the system tends in its motion towards a state with the lowest possible Gibbs free energy, it will prefer a state where the number of oriented water molecules is reduced. Thus the entropy term in the Gibbs free energy tends to make the "thermodynamic force" between two charges stronger, canceling at least part of the effect of the dielectric constant.

One can easily calculate the entropy of a system of N dipoles in an external field if one makes the simplifying assumption that the dipoles have only two quantum states, one parallel to the applied field, and the other antiparallel, differing by the energy $\Delta E = \mu F$. (F is the effective electric field acting on the dipole, i.e., it is due partly to the external field and partly to the fields of the other dipoles in the system.) then using the relation

$$S = \frac{E}{T} + k \ln Q \tag{2}$$

(where k is Boltzmann's constant, T is the temperature, E is the energy of the system, and Q is its partition function) we obtain

$$\begin{gathered} S = Nk\left(\frac{xe^{-x}}{1+e^{-x}} + \ln(1+e^{-x})\right), \\ x \equiv \frac{\Delta E}{kT} \end{gathered} \tag{3}$$

The behavior of this entropy as a function of x is as shown in Figure 1.

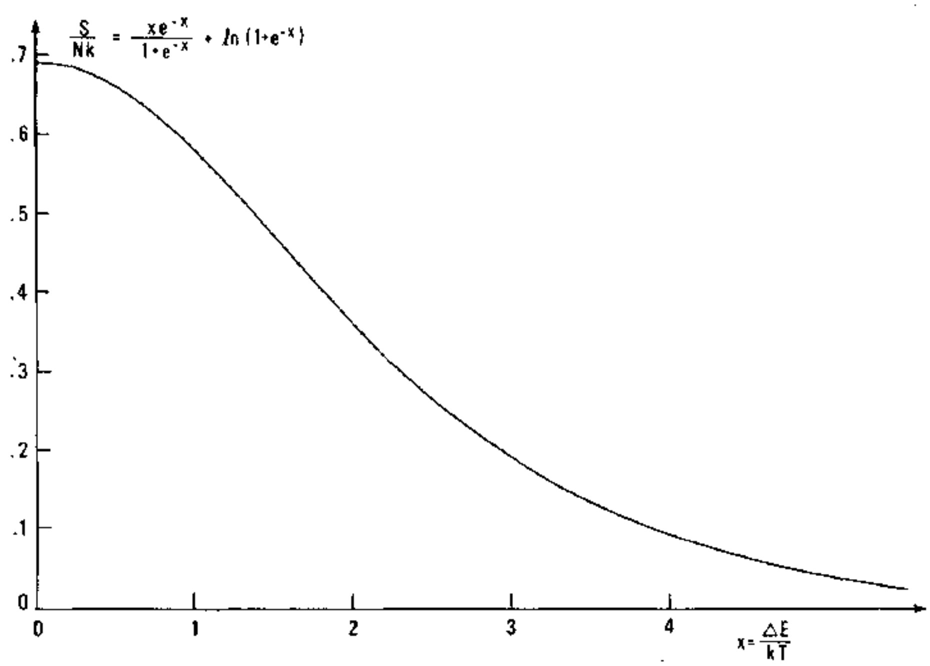

Figure 1. The entropy of a system of electric dipoles as a function of the electric field strength, under the simplifying assumption that the dipoles have only two possible quantum states, one parallel and the other antiparallel to the field.

The simple example discussed above cannot give us more than an extremely rough and qualitative picture of how the entropy of water behaves as a function of electric field strength. Some further insight can be obtained by considering the entropy change which takes place when ice *Ic* is placed in a strong electric field. Ice *Ic* (cubic ice) is a form of ice in which the oxygen atoms are arranged in a structure isomorphous with the arrangement of carbon in diamond [48].

Each oxygen atom in ice *Ic* is tetrahedrally hydrogen bonded to four other oxygen atoms. The distance between neighboring oxygen atoms is 2.76 Å.

In 1935, Linus Pauling [63, 64] published a paper on the low-temperature entropy of ice in which he argued that the water molecule is essentially intact in ice. In the gas phase, the H—O bond length in water is 0.95 Å. Pauling argued that "the magnitudes of changes in properties from steam to ice are not sufficiently great to permit us to assume that this distance is increased to 1.38 Å." Therefore, Pauling argued, in ice, a hydrogen atom between two oxygens is not placed midway between them, but is nearer to one than to the other. Pauling's hypothesis that the water molecule in ice is essentially intact was later confirmed by neutron diffraction experiments.

In his 1935 paper, Pauling showed that if the water molecules in ice are assumed to be essentially intact, the hydrogen-bonding system of the crystal can be formed in $(\frac{3}{2})^N$ different ways, where N is the number of water molecules in the crystal. He showed that this large variety of possible conformations of the crystal, none of which differs appreciably in energy from the others, gives rise to a residual low-temperature entropy of

$$\Delta S = Nk \ln (\tfrac{3}{2}) = 0.805Nk, \tag{4a}$$

where k is Boltzmann's constant. This calculated residual low-temperature entropy is close to the measured value of $0.87Nk$, an agreement which gives strong support to Pauling's theory.

Now let us consider what happens when ice is placed in an electric field which is strong enough to produce total orientation of the dipoles, but which nevertheless leaves the water molecules essentially intact. Can the water molecules reorient themselves in such a way that all the molecules have large components of their dipole moments pointing in the direction of the field, while still maintaining the hydrogen bonding system? From Figure 2, we can see that this is possible, but that there is only one possible configuration in which the dipoles are correctly oriented. In other words, in an electric field which is strong enough to produce total orientation of the water molecules, the residual low temperature entropy drops to zero, and the entropy change produced by applying the field is given by Eq. (4a). for smaller field strengths, the entropy would be difficult to calculate, but presumably it would fall off as a function of field strength in the manner of the entropy of the system of dipoles shown in Figure 1.

The two simple systems discussed above can give us a certain amount of qualitative insight into the behavior of the entropy of water as a function of applied electric field. However, it would be very desirable to have experimental determinations of the entropy and energy of water in strong electric fields. This information would be needed if one were to attempt to calculate the thermodynamic force between two charged particles in an aqueous medium.

If electrostatic forces are important in biological specificity, one might ask how far such forces extend. It might be possible to answer this question experimentally, starting with a knowledge of the diffusion constants of the molecules

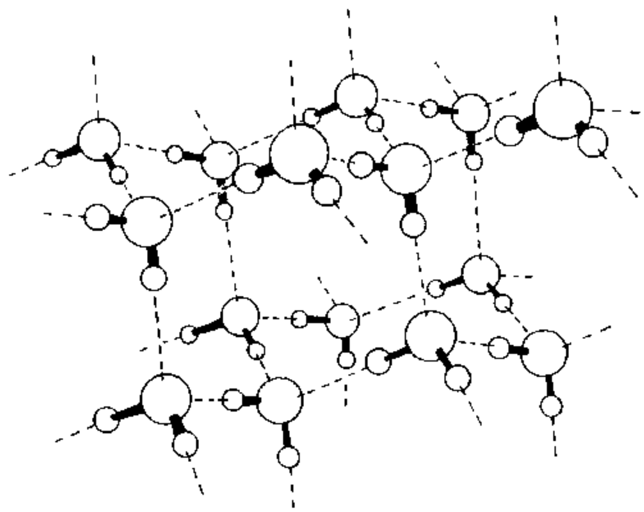

Figure 2. The hydrogen bonding system in ice *Ic*. When a strong electric field is applied, the molecules can orient themselves in such a way that each molecule has a large component of its dipole moment pointing in the direction of the field, while still maintaining the hydrogen bonding system. However, there is only one conformation in which this is possible (that shown in the figure); and thus, application of a strong electric field reduces the low-temperature residual entropy to zero.

involved in (for example) antigen-antibody reactions or enzyme-substrate reactions. It might then be possible to calculate the time which would be needed for binding under the assumption that the components had to reach the correct position and orientation by entirely random Brownian motion. The rate of binding could afterwards be calculated under the assumption that electrostatic forces reach out a certain distance into the solution, so that if the components diffuse to within a certain distance of one another, and to within a certain difference from the correct orientation, they will be trapped. In other words, the binding rate would be calculated under the assumption that if the reactants diffused to within a certain critical distance and critical error of orientation from the correct position, they would have very little probability of escaping, and would almost inevitably be drawn in and correctly oriented by electrostatic forces. These two binding rates could be compared with observed rates, and from this comparison, the degree to which electrostatic forces reach out into the solution and draw the components into place could be estimated.

Experiments and calculations might also be aimed at examination of the binding sites responsible for specificity, to determine whether or not electrostatic complementarity is involved. The crystallographic structures of a number of enzymes are known. For example, the structure of lysozyme has been determined by D. C. Phillips and co-workers [65]. As Professor Ricard has pointed out [35], the binding site of an enzyme is more closely complementary to an inhibitor than it is to the equilibrium conformation of its substrate. As the substrate of an enzyme-mediated reaction approaches the binding site, forces exerted by the site distort the substrate in the direction of the transition state, thus reducing the activation energy for the reaction. Notice that this picture implies the existence of forces which extend some distance out from the site. In cases where two reactants are joined together by an enzyme, such forces may help to guide the reactants together in the proper orientation, a mechanism which Koshland has called "orbital steering" [34].

From x-ray crystallographic data, it is possible to construct the electrostatic potential [66, 67]. To do this, one represents the charge density $\rho(x)$ by a Fourier series of the form:

$$\rho(\mathbf{x}) = \sum_{\mathbf{K}} (\rho)_{\mathbf{K}}\, e^{i\mathbf{K}\cdot\mathbf{x}}, \tag{4}$$

where the vectors $\mathbf{K}$ are reciprocal lattice vectors. Essentially, the Fourier coefficients $(\rho)_{\mathbf{K}}$ are what is measured in an x-ray diffraction experiment. Since the charge density and the electrostatic potential $\phi(\mathbf{x})$ are related through Poisson's equation:

$$\nabla^2\phi = -4\pi\rho. \tag{5}$$

It follows that if $\phi(\mathbf{x})$ is represented by the Fourier series

$$\phi(\mathbf{x}) = \sum_{\mathbf{K}} (\phi)_{\mathbf{K}}\, e^{i\mathbf{K}\cdot\mathbf{x}}, \tag{6}$$

the Fourier coefficients are related by

$$(\phi)_{\mathbf{K}} = \frac{4\pi}{K^2}(\rho)_{\mathbf{K}}. \tag{7}$$

Thus crystallographic measurements of Fourier coefficients of the charge density can be used to construct electrostatic fields. This method could be used to examine the active sites of enzymes to determine the electrostatic potentials near to the sites. Alternatively, it might be possible to calculate the charge distributions and potentials quantum mechanically, using methods such as those described by Professor McWeeny in his lecture [68–74].

I hope that future work in this direction will throw some light onto the phenomenon of biological specificity, one of the most widespread and fundamental phenomena in biology. In the meantime, I would tentatively put forward the view that in biological specificity, the molecules involved do not have to cover the entire distance to their binding sites by random diffusion. Perhaps during the last steps of the journey, they are guided into place by relatively long-range thermodynamic forces involving the entropy and energy of the intervening water molecules.

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Suggestions for further reading

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Chapter 12

WATER AND THE ORIGIN OF LIFE

12.1 Theories of chemical evolution towards the origin of life

The possibility of an era of chemical evolution prior to the origin of life entered the thoughts of Charles Darwin, but he considered the idea to be much too speculative to be included in his published papers and books. However, in February 1871, he wrote a letter to his close friend Sir Joseph Hooker containing the following words:

"It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, - light, heat, electricity etc. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured, or absorbed, which would not have been the case before living creatures were formed."

The last letter which Darwin is known to have dictated and signed before his death in 1882 also shows that he was thinking about this problem: "You have expressed quite correctly my views", Darwin wrote, "where you said that I had intentionally left the question of the Origin of Life uncanvassed as being altogether ultra vires in the present state of our knowledge, and that I dealt only with the manner of succession. I have met with no evidence that seems in the least trustworthy, in favor of so-called Spontaneous Generation. (However) I believe that I have somewhere said (but cannot find the passage) that the principle of continuity renders it probable that the principle of life will hereafter be shown to be a part, or consequence, of some general law.."

Modern researchers, picking up the problem where Darwin left it, have begun to throw a little light on the problem of chemical evolution towards the origin of life. In the 1930's J.B.S. Haldane in England and A.I. Oparin in Russia put forward theories of an era of chemical evolution prior to the appearance of living organisms.

In 1924 Oparin published a pamphlet on the origin of life. An expanded version of this pamphlet was translated into English and appeared in 1936 as a book entitled *The Origin of Life on Earth*. In this book Oparin pointed out that the time when life originated, conditions on earth were probably considerably different than they are at present: The atmosphere probably contained very little free oxygen, since free oxygen is produced by photosynthesis which did not yet exist. On the other hand, he argued, there were probably large amounts of methane and ammonia in the earth's primitive atmosphere[1]. Thus, before the origin of life, the earth probably had a reducing atmosphere rather than an oxidizing one. Oparin believed that energy-rich molecules could have been formed very slowly by the action of light from the sun. On the present-day earth, bacteria quickly consume energy-rich molecules, but before the origin of life, such molecules could have accumulated, since there were no living organisms to consume them. (This observation is similar to the remark made by Darwin in his 1871 letter to Hooker.)

The first experimental work in this field took place in 1950 in the laboratory of Melvin Calvin at the University of California, Berkeley. Calvin and his co-workers wished to determine experimentally whether the primitive atmosphere of the earth could have been converted into some of the molecules which are the building-blocks of living organisms. The energy needed to perform these conversions they imagined to be supplied by volcanism, radioactive decay, ultraviolet radiation, meteoric impacts, or by lightning strokes.

The earth is thought to be approximately 4.6 billion years old. At the time when Calvin and his co-workers were performing their experiments, the earth's primitive atmosphere was believed to have consisted primarily of hydrogen, water, ammonia, methane, and carbon monoxide, with a little carbon dioxide. A large quantity of hydrogen was believed to have been initially present in the primitive atmosphere, but it was thought to have been lost gradually over a period of time because the earth's gravitational attraction is too weak to effectively hold such a light and rapidly-moving molecule. However, Calvin and his group assumed sufficient hydrogen to be present to act as a reducing agent. In their 1950 experiments they subjected a mixture of hydrogen and carbon dioxide, with a catalytic amount of Fe^{2+}, to bombardment by fast particles from the Berkeley cyclotron. Their experiments resulted in a good yield of formic acid and a moderate yield of formaldehyde. (The fast particles from the cyclotron were designed to simulate an energy input from radioactive decay on the primitive earth.)

Two years later, Stanley Miller, working in the laboratory of Harold Urey at the University of Chicago, performed a much more refined experiment of the same type. In Miller's experiment, a mixture of the gases methane, ammonia, water and hydrogen was subjected to an energy input from an electric spark. Miller's apparatus was designed so that the gases were continuously circulated, passing first through the spark chamber, then through a water trap which removed the non-volatile water soluble products, and then back again through the spark chamber, and so on. The resulting products are shown as a function of time in Figure 12.2.

[1] It is now believed that the main constituents of the primordial atmosphere were carbon dioxide, water, nitrogen, and a little methane.

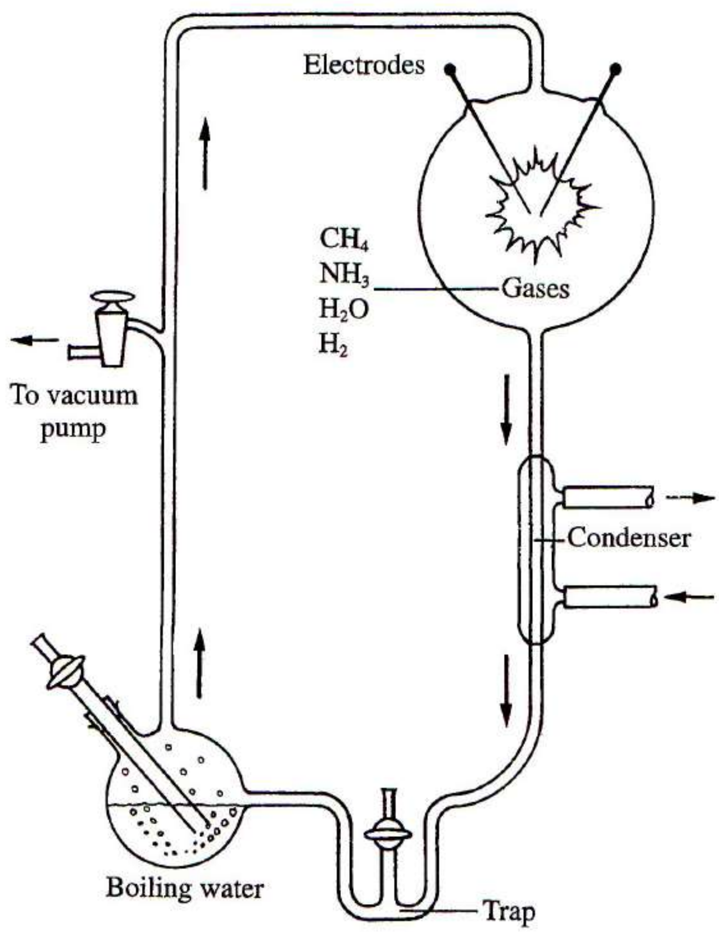

Figure 12.1: **Miller's apparatus.**

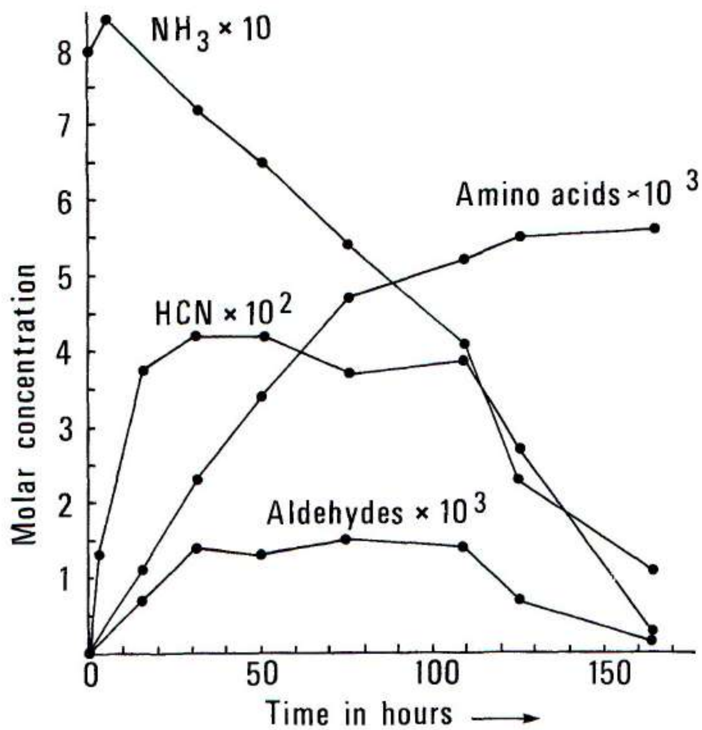

Figure 12.2: **Products as a function of time in the Miller-Urey experiment.**

The Miller-Urey experiment produced many of the building-blocks of living organisms, including glycine, glycolic acid, sarcosine, alanine, lactic acid, N-methylalanine, β-alanine, succinic acid, aspartic acid, glutamic acid, iminodiacetic acid, iminoacetic-propionic acid, formic acid, acetic acid, propionic acid, urea and N-methyl urea[2]. Another major product was hydrogen cyanide, whose importance as an energy source in chemical evolution was later emphasized by Calvin.

The Miller-Urey experiment was repeated and extended by the Ceylonese-American biochemist Cyril Ponnamperuma and by the American expert in planetary atmospheres, Carl Sagan. They showed that when phosphorus is made available, then in addition to amino acids, the Miller-Urey experiment produces not only nucleic acids of the type that join together to form DNA, but also the energy-rich molecule ATP (adenosine triphosphate). ATP is extremely important in biochemistry, since it is a universal fuel which drives chemical reactions inside present-day living organisms.

Further variations on the Miller-Urey experiment were performed by Sydney Fox and his co-workers at the University of Miami. Fox and his group showed that amino acids can be synthesized from a primitive atmosphere by means of a thermal energy input, and that in the presence of phosphate esters, the amino acids can be thermally joined together to form polypeptides. However, some of the peptides produced in this way were cross linked, and hence not of biological interest.

In 1969, Melvin Calvin published an important book entitled *Chemical Evolution; Molecular Evolution Towards the Origin of Living Systems on Earth and Elsewhere*. In this book, Calvin reviewed the work of geochemists showing the presence in extremely ancient rock formations of molecules which we usually think of as being produced only by living organisms. He then discussed experiments of the Miller-Urey type - experiments simulating the first step in chemical evolution. According to Calvin, not only amino acids but also the bases adenine, thymine, guanine, cytosine and uracil, as well as various sugars, were probably present in the primitive ocean in moderate concentrations, produced from the primitive atmosphere by the available energy inputs, and not broken down because no organisms were present.

The next steps visualized by Calvin were dehydration reactions in which the building blocks were linked together into peptides, polynucleotides, lipids and porphyrins. Such dehydration reactions are in a thermodynamically uphill direction. In modern organisms, they are driven by a universally-used energy source, the high-energy phosphate bond of adenosine triphosphate (ATP). Searching for a substance present in the primitive ocean which could have driven the dehydrations, Calvin and his coworkers experimented with hydrogen cyanide (HC=N), and from the results of these experiments they concluded that the energy stored in the carbon-nitrogen triple bond of HC=N could indeed have driven the dehydration reactions necessary for polymerization of the fundamental building blocks. However, later work made it seem improbable that peptides could be produced from cyanide mixtures.

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[2] The chemical reaction that led to the formation of the amino acids that Miller observed was undoubtedly the Strecker synthesis: $HCN + NH_3 + RC{=}O + H_2O \rightarrow RC(NH_2)COOH$.

In Chemical Evolution, Calvin introduced the concept of autocatalysis as a mechanism for molecular selection, closely analogous to natural selection in biological evolution. Calvin proposed that there were a few molecules in the ancient oceans which could catalyze the breakdown of the energy-rich molecules present into simpler products. According to Calvin's hypothesis, in a very few of these reactions, the reaction itself produced more of the catalyst. In other words, in certain cases the catalyst not only broke down the energy-rich molecules into simpler products but also catalyzed their own synthesis. These autocatalysts, according to Calvin, were the first systems which might possibly be regarded as living organisms. They not only "ate" the energy-rich molecules but they also reproduced - i.e., they catalyzed the synthesis of molecules identical with themselves.

Autocatalysis leads to a sort of molecular natural selection, in which the precursor molecules and the energy-rich molecules play the role of "food", and the autocatalytic systems compete with each other for the food supply. In Calvin's picture of molecular evolution, the most efficient autocatalytic systems won this competition in a completely Darwinian way. These more efficient autocatalysts reproduced faster and competed more successfully for precursors and for energy-rich molecules. Any random change in the direction of greater efficiency was propagated by natural selection.

What were these early autocatalytic systems, the forerunners of life? Calvin proposed several independent lines of chemical evolution, which later, he argued, joined forces. He visualized the polynucleotides, the polypeptides, and the metallo-porphyrins as originally having independent lines of chemical evolution. Later, he argued, an accidental union of these independent autocatalysts showed itself to be a still more efficient autocatalytic system. He pointed out in his book that "autocatalysis" is perhaps too strong a word. One should perhaps speak instead of "reflexive catalysis" , where a molecule does not necessarily catalyze the synthesis of itself, but perhaps only the synthesis of a precursor. Like autocatalysis, reflexive catalysis is capable of exhibiting Darwinian selectivity.

The theoretical biologist, Stuart Kauffman, working at the Santa Fe Institute, has constructed computer models for the way in which the components of complex systems of reflexive catalysts may have been linked together. Kauffman's models exhibit a surprising tendency to produce orderly behavior even when the links are randomly programmed.

In 1967 and 1968, C. Woese, F.H.C. Crick and L.E. Orgel proposed that there may have been a period of chemical evolution involving RNA alone, prior to the era when DNA, RNA and proteins joined together to form complex self-reproducing systems. In the early 1980's, this picture of an "RNA world" was strengthened by the discovery (by Thomas R. Cech and Sydney Altman) of RNA molecules which have catalytic activity.

Today experiments aimed at throwing light on chemical evolution towards the origin of life are being performed in the laboratory of the Nobel Laureate geneticist Jack Sjostak at Harvard Medical School. The laboratory is trying to build a synthetic cellular system that undergoes Darwinian evolution.

In connection with autocatalytic systems, it is interesting to think of the polymerase chain reaction, which we discussed above. The target segment of DNA and the polymerase together form an autocatalytic system. The "food" molecules are the individual nucleotides in the solution. In the PCR system, a segment of DNA reproduces itself with an extremely high degree of fidelity. One can perhaps ask whether systems like the PCR system can have been among the forerunners of living organisms. The cyclic changes of temperature needed for the process could have been supplied by the cycling of water through a hydrothermal system. There is indeed evidence that hot springs and undersea hydrothermal vents may have played an important role in chemical evolution towards the origin of life. We will discuss this evidence in the next section.

Throughout this discussion of theories of chemical evolution, and the experiments which have been done to support these theories, energy has played a central role. None of the transformations discussed above could have taken place without an energy source, or to be more precise, they could not have taken place without a source of free energy.

Molecular evidence establishing family trees in evolution

Starting in the 1970's, the powerful sequencing techniques developed by Sanger and others began to be used to establish evolutionary trees. The evolutionary closeness or distance of two organisms could be estimated from the degree of similarity of the amino acid sequences of their proteins, and also by comparing the base sequences of their DNA and RNA. One of the first studies of this kind was made by R.E. Dickerson and his coworkers, who studied the amino acid sequences in Cytochrome C, a protein of very ancient origin which is involved in the "electron transfer chain" of respiratory metabolism. Some of the results of Dickerson's studies are shown in Figure 12.3.

Comparison of the base sequences of RNA and DNA from various species proved to be even more powerful tool for establishing evolutionary relationships. Figure 12-4 shows the universal phylogenetic tree established in this way by Iwabe, Woese and their coworkers.[3] In Figure 12.4, all presently living organisms are divided into three main kingdoms, Eukaryotes, Eubacteria, and Archaebacteria. Carl Woese, who proposed this classification on the basis of comparative sequencing, wished to call the three kingdoms "Eucarya, Bacteria and Archaea". However, the most widely accepted terms are the ones shown in capital letters on the figure. Before the comparative RNA sequencing work, which was performed on the ribosomes of various species, it had not been realized that there are two types of bacteria, so markedly different from each other that they must be classified as belonging to separate kingdoms. One example of the difference between archaebacteria and eubacteria is that the former have cell membranes which contain ether lipids, while the latter have ester lipids in their cell membranes. Of the three kingdoms, the eubacteria and the archaebacteria are "prokaryotes", that is to say, they are unicellular organisms having no cell nucleus. Most of the eukaryotes, whose cells contain a nucleus, are also unicellular, the exceptions being plants, fungi and animals.

One of the most interesting features of the phylogenetic tree shown in Figure 12.4 is that the deepest branches - the organisms with shortest pedigrees - are all hyperhermophiles,

[3] "Phylogeny" means "the evolutionary development of a species". "Ontogeny" means "the growth and development an individual, through various stages, for example, from fertilized egg to embryo, and so on." Ernst Haeckel, a 19th century follower of Darwin, observed that, in many cases, "ontogeny recapitulates phylogeny."

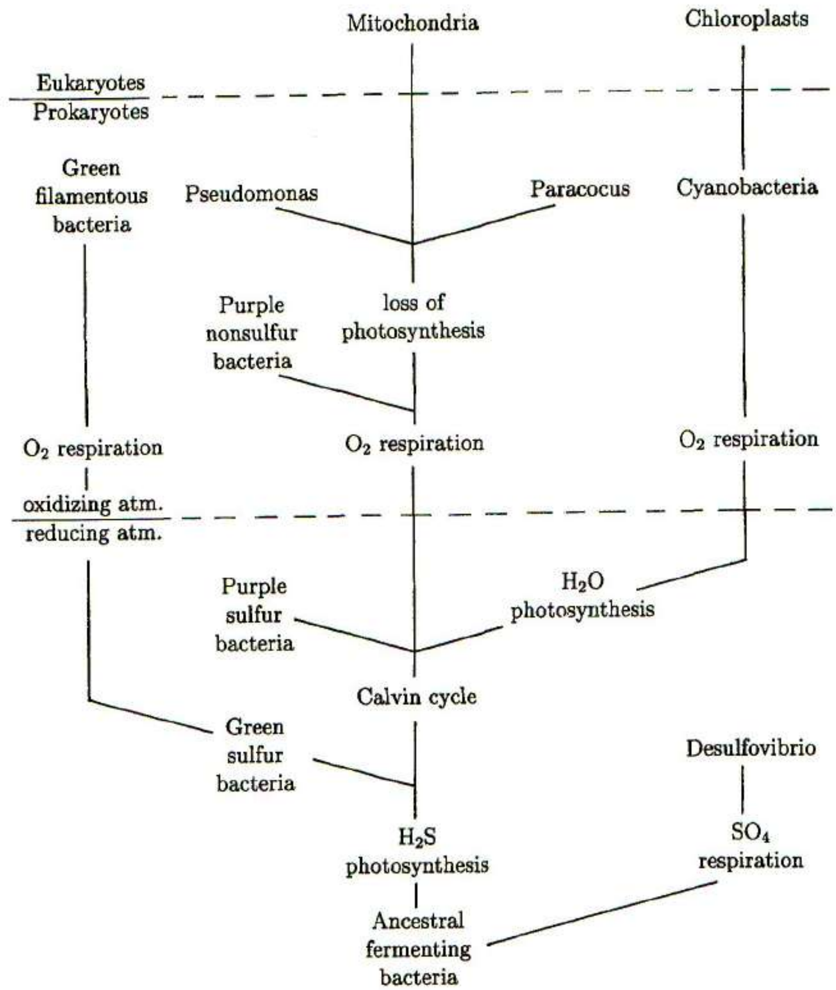

Figure 12.3: **Evolutionary relationships established by Dickerson and coworkers by comparing the amino acid sequences of Cytochrome C from various species.**

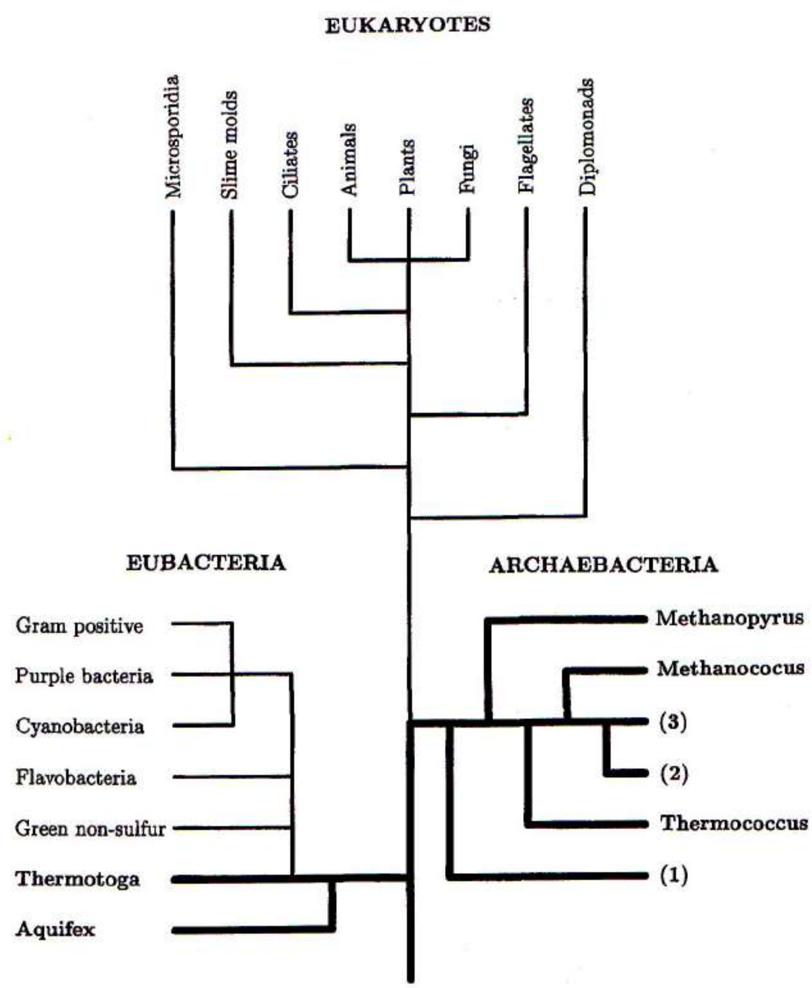

Figure 12.4: **This figure shows the universal phylogenetic tree, established by the work of Woese, Iwabe et al. Hyperthermophiles are indicated by bold lines and by bold type.**

i.e. they live in extremely hot environments such as hot springs or undersea hydrothermal vents. The shortest branches represent the most extreme hyperthermophiles. The group of archaebacteria indicated by (1) in the figure includes *Thermofilum, Thermoproteus, Pyrobaculum, Pyrodictium, Desulfurococcus*, and *Sulfolobus* - all hypothermophiles[4]. Among the eubacteria, the two shortest branches, Aquifex and Thermatoga are both hyperthermophiles[5]

The phylogenetic evidence for the existence of hyperthermophiles at a very early stage of evolution lends support to a proposal put forward in 1988 by the German biochemist Günter Wächterhäuser. He proposed that the reaction for pyrite formation,

$$FeS + H_2S \rightarrow FeS_2 + 2H + +2e^-$$

which takes place spontaneously at high temperatures, supplied the energy needed to drive the first stages of chemical evolution towards the origin of life. Wächterhäuser pointed out that the surface of the mineral pyrite (FeS_2) is positively charged, and he proposed that, since the immediate products of carbon-dioxide fixation are negatively charged, they would be attracted to the pyrite surface. Thus, in Wächterhäuser's model, pyrite formation not only supplied the reducing agent needed for carbon-dioxide fixation, but also the pyrite surface aided the process. Wächterhäuser further proposed an archaic autocatylitic carbon-dioxide fixation cycle, which he visualized as resembling the reductive citric acid cycle found in present-day organisms, but with all reducing agents replaced by FeS + H_2S, with thioester activation replaced by thioacid activation, and carbonyl groups replaced by thioenol groups. The interested reader can find the details of Wächterhäuser's proposals in his papers, which are listed at the end of this chapter.

A similar picture of the origin of life has been proposed by Michael J. Russell and Alan J. Hall in 1997. In this picture "...(i) life emerged as hot, reduced, alkaline, sulphide-bearing submarine seepage waters interfaced with colder, more oxidized, more acid, $Fe^{2+} >> Fe^{3+}$-bearing water at deep (*ca.* 4km) floors of the Hadian ocean *ca.* 4 Gyr ago; (ii) the difference in acidity, temperature and redox potential provided a gradient of pH (*ca.* 4 units), temperature (*ca.* 60°C) and redox potential (*ca.* 500 mV) at the interface of those waters that was sustainable over geological time-scales, providing the continuity of conditions conducive to organic chemical reactions needed for the origin of life..." [6]. Russell, Hall and their coworkers also emphasize the role that may have been played by spontaneously-formed 3-dimensional mineral chambers (bubbles). They visualize these as having prevented the reacting molecules from diffusing away, thus maintaining high concentrations.

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[4] Group (2) in Figure 12.4 includes *Methanothermus*, which is hyperthermophilic, and Methanobacterium, which is not. Group (3) includes *Archaeoglobus*, which is hyperthermophilic, and Halococcus, Halobacterium, Methanoplanus, Methanospirilum, and Methanosarcina, which are not.

[5] Thermophiles are a subset of the larger group of extremophiles.

[6] See W. Martin and M.J. Russell, *On the origins of cells: a hypothesis for the evolutionary transitions from abiotic geochemistry to chemoautotrophic prokaryotes, and from prokaryotes to nucleated cells*, Philos. Trans. R. Soc. Lond. B Biol. Sci., *358*, 59-85, (2003).

Table 12.1: **Energy-yielding reactions of some lithoautotrophic hyperthermophiles. (After K.O. Setter)**

Energy-yielding reaction	Genera
$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	Methanopyrus, Methanothermus, Methanococcus
$H_2 + S^\circ \rightarrow H_2S$	Pyrodictium, Thermoproteus, Pyrobaculum, Acidianus, Stygiolobus
$4H_2 + H_2SO_4 \rightarrow H_2S + 4H_2O$	Archaeoglobus

Table 12.1 shows the energy-yielding reactions which drive the metabolisms of some organisms which are of very ancient evolutionary origin. All the reactions shown in the table make use of H_2, which could have been supplied by pyrite formation at the time when the organisms evolved. All these organisms are lithoautotrophic, a word which requires some explanation: A heterotrophic organism is one which lives by ingesting energy-rich organic molecules which are present in its environment. By contrast, an autotrophic organism ingests only inorganic molecules. The lithoautotrophs use energy from these inorganic molecules, while the metabolisms of photoautotrophs are driven by energy from sunlight.

Evidence from layered rock formations called "stromatolites", produced by colonies of photosynthetic bacteria, show that photoautotrophs (or phototrophs) appeared on earth at least 3.5 billion years ago. The geological record also supplies approximate dates for other events in evolution. For example, the date at which molecular oxygen started to become abundant in the earth's atmosphere is believed to have been 2.0 billion years ago, with equilibrium finally being established 1.5 billion years in the past. Multi-cellular organisms appeared very late on the evolutionary and geological time-scale - only 600 million years ago. By collecting such evidence, the Belgian cytologist Christian de Duve has constructed the phylogenetic tree shown in Figure 12.5, showing branching as a function of time. One very interesting feature of this tree is the arrow indicating the transfer of "endosymbionts" from the eubacteria to the eukaryotes. In the next section, we will look in more detail at this important event, which took place about 1.8 billion years ago.

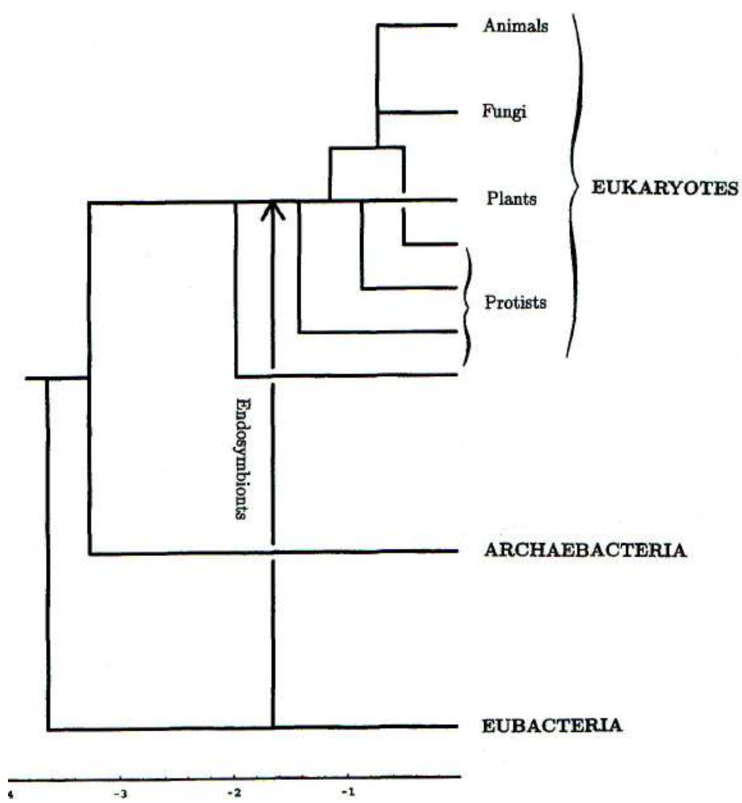

Figure 12.5: **Branching of the universal phylogenetic tree as a function of time. "Protists" are unicellular eukaryotes.**

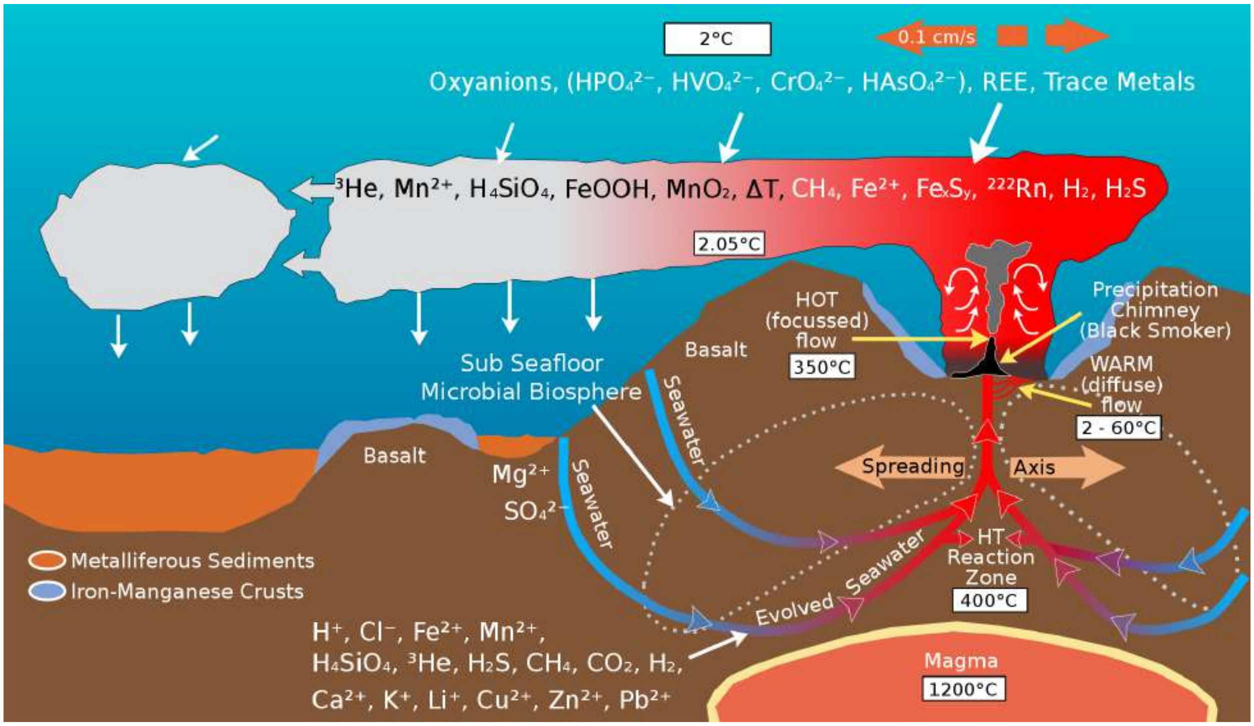

Figure 12.6: **Deep-sea vent biogeochemical cycle diagram.**

Figure 12.7: **Giant tube worms (Riftia pachyptila) cluster around vents in the Galapagos Rift.**

Symbiosis

The word “symbiosis” is derived from Greek roots meaning “living together”. It was coined in 1877 by the German botanist Albert Bernard Frank. By that date, it had become clear that lichens are composite organisms involving a fungus and an alga; but there was controversy concerning whether the relationship was a parasitic one. Was the alga held captive and exploited by the fungus? Or did the alga and the fungus help each other, the former performing photosynthesis, and the latter leeching minerals from the lichen’s environment? In introducing the word “symbiosis” (in German, “Symbiotismus”), Prank remarked that “We must bring all the cases where two different species live on or in one another under a comprehensive concept which does not consider the role which the two individuals play but is based on the mere coexistence, and for which the term symbiosis is to be recommended.” Thus the concept of symbiosis, as defined by Frank, included all intimate relationships between two or more species, including parasitism at one extreme and “mutualism” at the other. However, as the word is used today, it usually refers to relationships which are mutually beneficial.

Charles Darwin himself had been acutely aware of close and mutually beneficial relationships between organisms of different species. For example, in his work on the fertilization of flowers, he had demonstrated the way in which insects and plants can become exquisitely adapted to each other’s needs. However, T.H. Huxley, “Darwin’s bulldog”, emphasized competition as the predominant force in evolution. “The animal world is on about the same level as a gladiator’s show”, Huxley wrote in 1888, “The creatures are fairly well treated and set to fight - whereby the strongest, the swiftest and the cunningest live to fight another day. The spectator has no need to turn his thumbs down, as no quarter is given.” The view of nature as a sort of ”gladiator’s contest” dominated the mainstream of evolutionary thought far into the 20th century; but there was also a growing body of opinion which held that symbiosis could be an extremely important mechanism for the generation of new species.

Among the examples of symbiosis studied by Frank were the nitrogen-fixing bacteria living in nodules on the roots of legumes, and the mycorrhizal fungi which live on the roots of forest trees such as oaks, beech and conifers. Frank believed that the mycorrhizal fungi aid in the absorption of nutrients. He distinguished between “ectotrophic” fungi, which form sheaths around the root fibers, and “endotrophic” fungi, which penetrate the root cells. Other examples of symbiosis studied in the 19th century included borderline cases between plants and animals, for example, paramecia, sponges, hydra, planarian worms and sea anemones, all of which frequently contain green bodies capable of performing photosynthesis.

Writing in 1897, the American lichenologist Albert Schneider prophesied that “future studies may demonstrate that.., plasmic bodies (within the eukaryote cell), such as chlorophyll granules, leucoplastids, chromoplastids, chromosomes, centrosomes, nucleoli, etc., are perhaps symbionts comparable to those in less highly specialized symbiosis. Reinke expresses the opinion that it is not wholly unreasonable to suppose that some highly skilled scientist of the future may succeed in cultivating chlorophyll-bodies in artificial media.”

19th century cytologists such as Robert Altman, Andreas Schimper and A. Benda focused attention on the chlorophyll-bodies of plants, which Schimper named chloroplasts, and on another type of subcellular granule, present in large numbers in all plant and animal cells, which Benda named mitochondria, deriving the name from the Greek roots mitos (thread) and chrondos (granule). They observed that these bodies seemed to reproduce themselves within the cell in very much the manner that might be expected if they were independent organisms. Schimper suggested that chloroplasts are symbionts, and that green plants owe their origin to a union of a colorless unicellular organism with a smaller chlorophyll-containing species.

The role of symbiosis in evolution continued to be debated in the 20th century. Mitochondria were shown to be centers of respiratory metabolism; and it was discovered that both mitochondria and chloroplasts contain their own DNA. However, opponents of their symbiotic origin pointed out that mitochondria alone cannot synthesize all their own proteins: Some mitochondrial proteins require information from nuclear DNA. The debate was finally settled in the 1970's, when comparative sequencing of ribosomal RNA in the laboratories of Carl Woese, W. Ford Doolittle and Michael Gray showed conclusively that both chloroplasts and mitochondria were originally endosymbionts. The ribosomal RNA sequences showed that chloroplasts had their evolutionary root in the cyanobacteria, a species of eubacteria, while mitochondria were traced to a group of eubacteria called the alpha-proteobacteria. Thus the evolutionary arrow leading from the eubacteria to the eukaryotes can today be drawn with confidence, as in Figure 12.5.

Cyanobacteria are bluish photosynthetic bacteria which often become linked to one another so as to form long chains. They can be found today growing in large colonies on seacoasts in many parts of the world, for example in Baja California on the Mexican coast. The top layer of such colonies consists of the phototrophic cyanobacteria, while the organisms in underlying layers are heterotrophs living off the decaying remains of the cyanobacteria. In the course of time, these layered colonies can become fossilized, and they are the source of the layered rock formations called stromatolites (discussed above). Geological dating of ancient stromatolites has shown that cyanobacteria must have originated at least 3.5 billion years ago.

Cyanobacteria contain two photosystems, each making use of a different type of chlorophyll. Photosystem I, which is thought to have evolved first, uses the energy of light to draw electrons from inorganic compounds, and sometimes also from organic compounds (but never from water). Photosystem II, which evolved later, draws electrons from water. Hydrogen derived from the water is used to produce organic compounds from carbon-dioxide, and molecular oxygen is released into the atmosphere. Photosystem II never appears alone. In all organisms which possess it, Photosystem II is coupled to Photosystem I, and together the two systems raise electrons to energy levels that are high enough to drive all the processes of metabolism. Dating of ancient stromatolites makes it probable that cyanobacteria began to release molecular oxygen into the earth's atmosphere at least 3.5 billion years ago; yet from other geological evidence we know that it was only 2 billion years ago that the concentration of molecular oxygen began to rise, equilibrium being reached 1.5 billion years ago. It is believed that ferrous iron, which at one time was very abundant, initially absorbed the photosynthetically produced oxygen. This resulted in the time-lag, as well as the ferrous-ferric mixture of iron which is found in the mineral magnetite.

When the concentrations of molecular oxygen began to rise in earnest, most of the unicellular microorganisms living at the time found themselves in deep trouble, faced with extinction, because for them oxygen was a deadly poison; and very many species undoubtedly perished. However, some of the archaebacteria retreated to isolated anaerobic niches where we find them today, while others found ways of detoxifying the poisonous oxygen. Among the eubacteria, the ancestors of the alpha-proteobacteria were particularly good at dealing with oxygen and even turning it to advantage: They developed the biochemical machinery needed for respiratory metabolism.

Meanwhile, during the period between 3.5 and 2.0 billion years before the present, an extremely important evolutionary development had taken place: Branching from the archaebacteria, a line of large[7] heterotrophic unicellular organisms had evolved. They lacked rigid cell walls, and they could surround smaller organisms with their flexible outer membrane, drawing the victims into their interiors to be digested. These new heterotrophs were the ancestors of present-day eukaryotes, and thus they were the ancestors of all multicellular organisms.

Not only are the cells of present-day eukaryotes very much larger than the cells of archaebacteria and eubacteria; their complexity is also astonishing. Every eukaryote cell contains numerous intricate structures: a nucleus, cytoskeleton, Golgi apparatus, endoplasmic reticulum, mitochondria, peroxisomes, chromosomes, the complex structures needed for mitotic cell division, and so on. Furthermore, the genomes of eykaryotes contain very much more information than those of prokaryotes. How did this huge and relatively sudden increase in complexity and information content take place? According to a growing body of opinion, symbiosis played an important role in this development.

The ancestors of the eukaryotes were in the habit of drawing the smaller prokaryotes into their interiors to be digested. It seems likely that in a few cases the swallowed prokaryotes resisted digestion, multiplied within the host, were transmitted to future generations when the host divided, and conferred an evolutionary advantage, so that the result was a symbiotic relationship. In particular, both mitochondria and chloroplasts have definitely been proved to have originated as endosymbionts. It is easy to understand how the photosynthetic abilities of the chloroplasts (derived from cyanobacteria) could have conferred an advantage to their hosts, and how mitochondria (derived from alpha-proteobacteria) could have helped their hosts to survive the oxygen crisis. The symbiotic origin of other sub-cellular organelles is less well understood and is currently under intense investigation.

If we stretch the definition of symbiosis a little, we can make the concept include cooperative relationships between organisms of the same species. For example, cyanobacteria join together to form long chains, and they live together in large colonies which later turn into stromatolites. Also, some eubacteria have a mechanism for sensing how many of their species are present, so that they know, like a wolf pack, when it is prudent to attack a

[7] not large in an absolute sense, but large in relation to the prokaryotes

larger organism. This mechanism, called "quorum sensing", has recently attracted much attention among medical researchers.

The cooperative behavior of a genus of unicellular eukaryotes called slime molds is particularly interesting because it gives us a glimpse of how multicellular organisms may have originated. The name of the slime molds is misleading, since they are not fungi, but heterotrophic protists similar to amoebae. Under ordinary circumstances, the individual cells wander about independently searching for food, which they draw into their interiors and digest, a process called "phagocytosis". However, when food is scarce, they send out a chemical signal of distress. Researchers have analyzed the molecule which expresses slime mold unhappiness, and they have found it to be cyclic adenosine monophosphate (cAMP). At this signal, the cells congregate and the mass of cells begins to crawl, leaving a slimy trail. As it crawls, the community of cells gradually develops into a tall stalk, surmounted by a sphere - the "fruiting body". Inside the sphere, spores are produced by a sexual process. If a small animal, for example a mouse, passes by, the spores may adhere to its coat; and in this way they may be transported to another part of the forest where food is more plentiful.

Thus slime molds represent a sort of missing link between unicellular and multicellular or organisms. Normally the cells behave as individualists, wandering about independently, but when challenged by a shortage of food, the slime mold cells join together into an entity which closely resembles a multicellular organism. The cells even seem to exhibit altruism, since those forming the stalk have little chance of survival, and yet they are willing to perform their duty, holding up the sphere at the top so that the spores will survive and carry the genes of the community into the future. We should especially notice the fact that the cooperative behavior of the slime mold cells is coordinated by chemical signals.

Sponges are also close to the borderline which separates unicellular eukaryotes (protists) from multicellular organisms, but they are just on the other side of the border. Normally the sponge cells live together in a multicellular community, filtering food from water. However, if a living sponge is forced through a very fine cloth, it is possible to separate the cells from each other. The sponge cells can live independently for some time; but if many of them are left near to one another, they gradually join together and form themselves into a new sponge, guided by chemical signals. In a refinement of this experiment, one can take two living sponges of different species, separate the cells by passing the sponges through a fine cloth, and afterwards mix all the separated cells together. What happens next is amazing: The two types of sponge cells sort themselves out and become organized once more into two sponges - one of each species.

Slime molds and sponges hint at the genesis of multicellular organisms, whose evolution began approximately 600 million years ago. Looking at the slime molds and sponges, we can imagine how it happened. Some unicellular organisms must have experienced an enhanced probability of survival when they lived as colonies. Cooperative behavior and division of labor within the colonies were rewarded by the forces of natural selection, with the selective force acting on the entire colony of cells, rather than on the individual cell. This resulted in the formation of cellular societies and the evolution of mechanisms for cell differentiation. The division of labor within cellular societies (i.e., differentiation) came to be coordinated by chemical signals which affected the transcription of genetic information and the synthesis of proteins. Each cell within a society of cells possessed the entire genome characteristic of the colony, but once a cell had been assigned its specific role in the economy of the society, part of the information became blocked - that is, it was not expressed in the function of that particular cell. As multicellular organisms evolved, the chemical language of intercellular communication became very much more complex and refined. We will discuss the language of intercellular communication in more detail in a later section.

Geneticists have become increasingly aware that symbiosis has probably played a major role in the evolution of multicellular organisms. We mentioned above that, by means of genetic engineering techniques, transgenic plants and animals can be produced. In these chimeras, genetic material from a foreign species is incorporated into the chromosomes, so that it is inherited in a stable, Mendelian fashion. J.A. Shapiro, one of whose articles is referenced at the end of this chapter, believes that this process also occurs in nature, so that the conventional picture of evolutionary family trees needs to be corrected. Shapiro believes that instead of evolutionary trees, we should perhaps think of webs or networks.

For example, it is tempting to guess that symbiosis may have played a role in the development of the visual system of vertebrates. One of the archaebacteria, the purple halobacterium halobium (recently renamed halobacterium salinarum), is able to perform photosynthesis by means of a protein called bacterial rhodopsin, which transports hydrogen ions across the bacterial membrane. This protein is a near chemical relative of rhodopsin, which combines with a carotinoid to form the "visual purple" used in the vertebrate eye. It is tempting to think that the close similarity of the two molecules is not just a coincidence, and that vertebrate vision originated in a symbiotic relationship between the photosynthetic halobacterium and an aquatic ancestor of the vertebrates, the host being able to sense when the halobacterium was exposed to light and therefore transporting hydrogen ions across its cell membrane.

12.2 Water on Mars; Life on Mars?

Water on Mars, now and in the past

Even today, there is a great deal of water on Mars, frozen, under the crust. There is enough to cover the entire planet in a layer of water more than 300 meters deep. Huwever, in the past, the amount of water on Mars was vastly greater. Most scientists believe that when Mars lost most of its atmosphere, it also lost much of its water.

Why did Mars lose its atmosphere?

According to one theory, Mars once had a strong magnetic field, like the Earth. This strong magnetic field deflected the "solar wind", the streem of charged particles from the sun. However, when the core of the plabet solidified, Mars lost most of its magnetic field,

Figure 12.8: **NASA's Thomas Zurbuchen announced the rover's official name, Perseverance, on 5 March 2020, at Lake Braddock Secondary School in Burke, Virginia. Zurbuchen made the final selection following a 2019 nationwide naming contest that drew more than 28,000 essays by K-12 students from every U.S. state and territory.**

and the solar wind supplied the energy that resulted in the loss of Mars' atmosphere, and most of its water.

Life on Mars

Since the conditions on Mars were once very similar to those on the Earth, it seems very probable that life also evolved there. The question is whether some form of life still exists on Mars today, now that the planet has almost no atmosphere, and with conditions so much harsher. Although no conclusive evidence of current life on Mars has yet been found, several recent probes have been designed to search for bacteria-like organisms under the frozen surface.

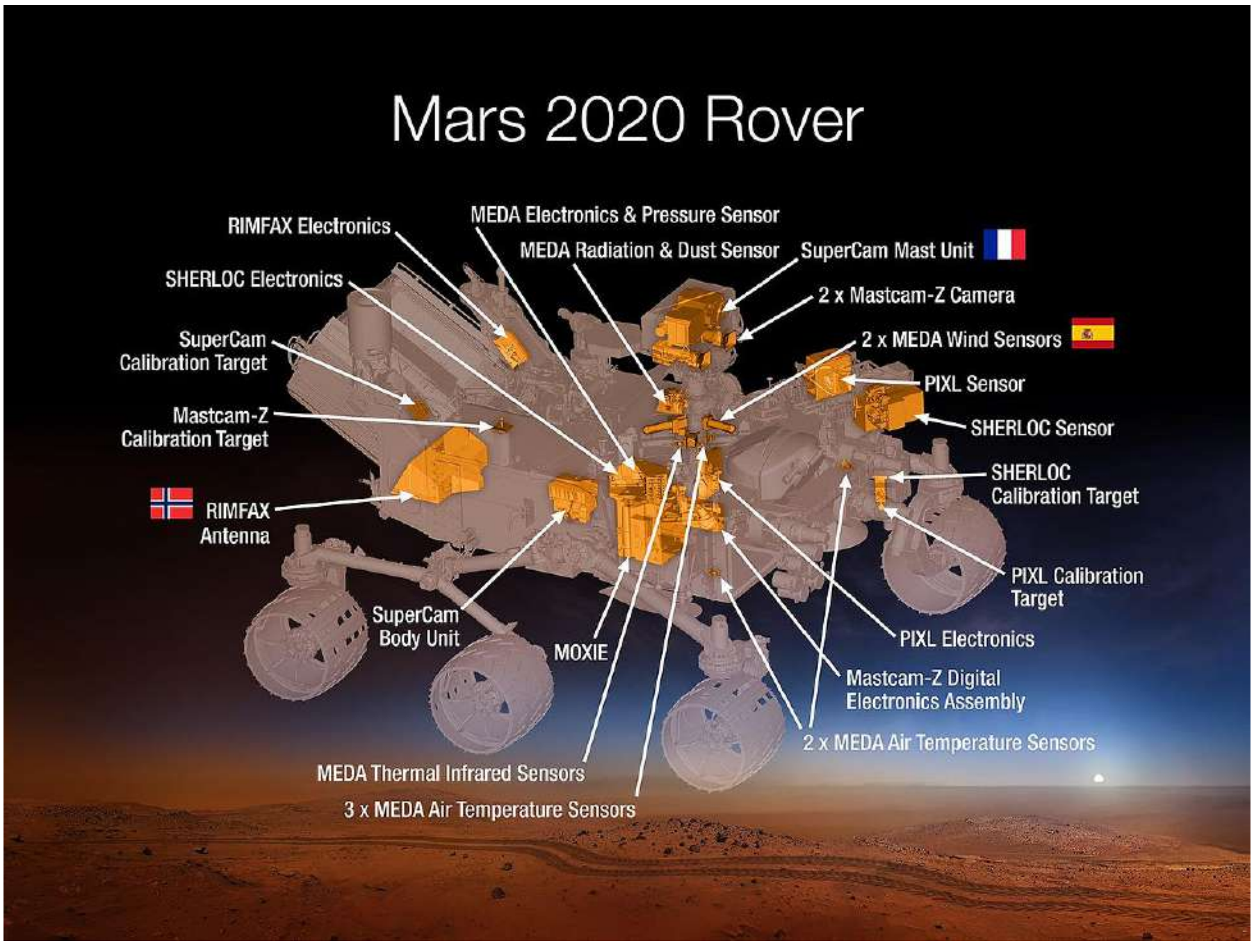

Figure 12.9: **Diagram illustrating the locations of scientific instruments aboard Perseverance**

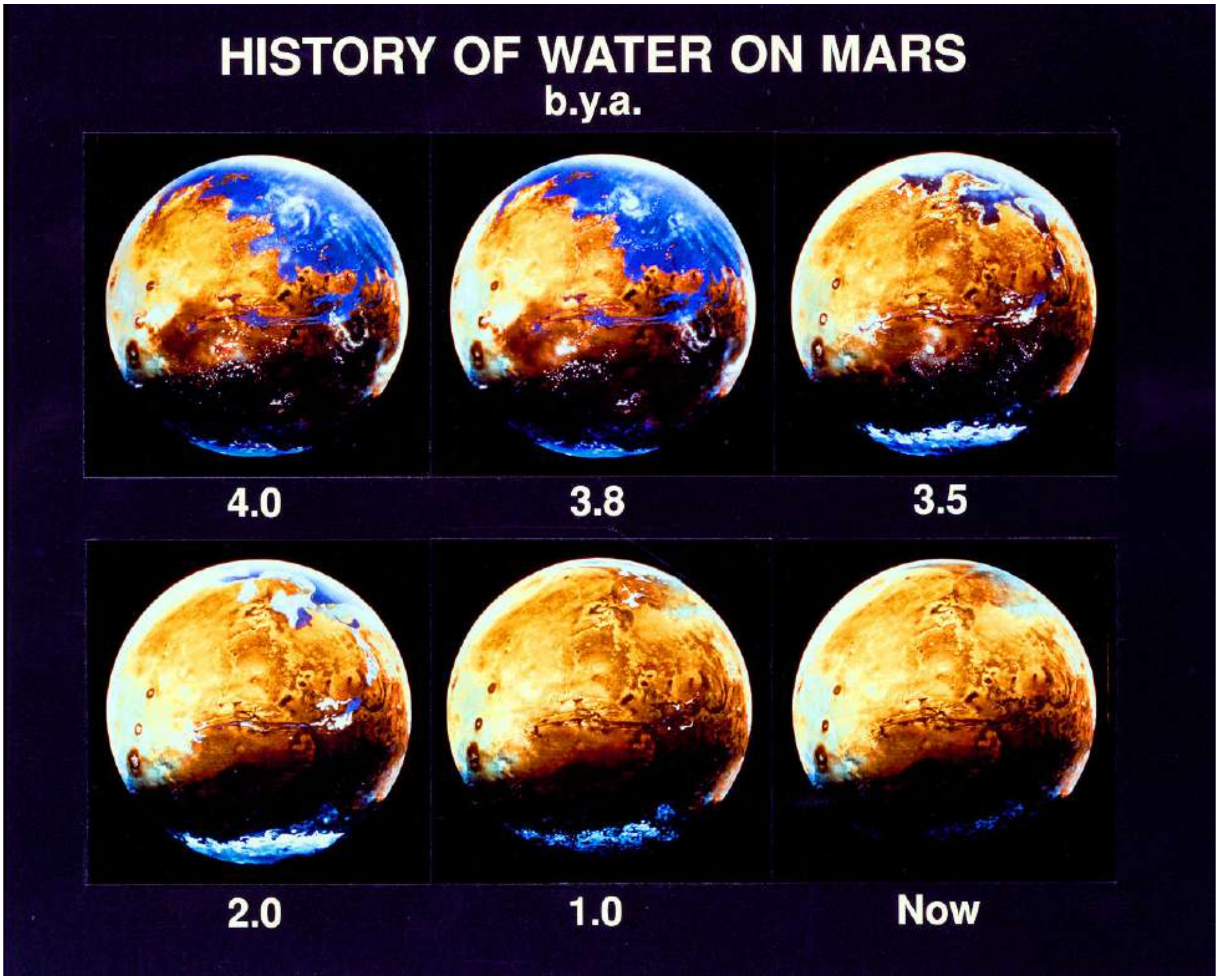

Figure 12.10: **History of water on Mars. Numbers represent how many billions of years ago.**

Astrobiology

Astrobiology is an interdisciplinary field of study which aims at exploring the conditions needed for life throughout the universe. Astrobiologists often make two simplifying assumptions. Firstly they assume life-forms to be carbon-based, and secondly they assume that water must be present, in order to facilitate carbon-based chemistry. These assumptions are made to narrow the field of investigation and to make it more manageable, but it is not absolutely necessary to assume that life must be carbon-based, or that liquid water must be present. For example, the possible existence of silicon-based life-forms has been proposed by some scientists.

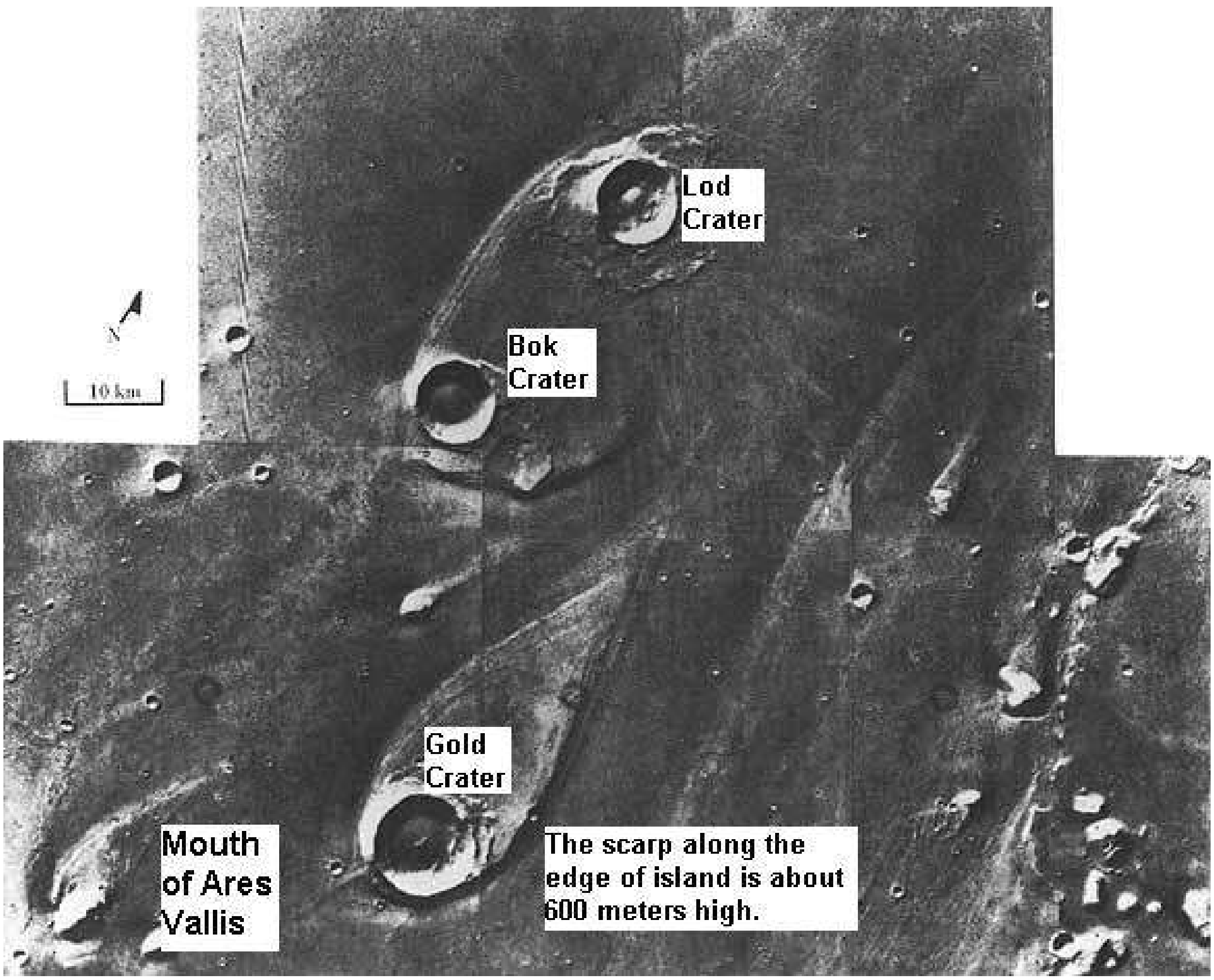

Figure 12.11: **Tear-drop shaped islands carved by flood waters from Ares Vallis. (Oxia Palus quadrangle) Photo from NASA Viking Program.**

12.3 Life elsewhere in the universe

On December 18, 2017, scientists from the University of California published an article in *Science News* entitled *Ancient fossil microorganisms indicate that life in the universe is common.* According to the article:

"A new analysis of the oldest known fossil microorganisms provides strong evidence to support an increasingly widespread understanding that life in the universe is common.

"The microorganisms, from Western Australia, are 3.465 billion years old. Scientists from UCLA and the University of Wisconsin-Madison report today in the journal Proceedings of the National Academy of Sciences that two of the species they studied appear to have performed a primitive form of photosynthesis, another apparently produced methane gas, and two others appear to have consumed methane and used it to build their cell walls.

"The evidence that a diverse group of organisms had already evolved extremely early in the Earth's history, combined with scientists' knowledge of the vast number of stars in the universe and the growing understanding that planets orbit so many of them, strengthens the case for life existing elsewhere in the universe because it would be extremely unlikely that life formed quickly on Earth but did not arise anywhere else."

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