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Emerging Challenges – New Findings

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- EMERGING AND RE-EMERGING INFECTIOUS DISEASES: LINKS TO ENVIRONMENTAL CHANGE
- ABRUPT CLIMATE CHANGE: OCEAN SALINITY CHANGES AND POTENTIAL IMPACTS ON OCEAN CIRCULATION

Emerging Challenges – New Findings

This section presents some of the latest evidence from scientific research that can shed new light on ongoing and emerging environmental complexities and priority issues. This year's issues – the links between environmental change and emerging and re-emerging infectious diseases, and the possible consequences of reduced ocean salinity – were identified in consultation with the Scientific Committee on Problems of the Environment (SCOPE) of the International Council for Science (ICSU).

Emerging and Re-emerging Infectious Diseases: Links to Environmental Change

Environmental factors are major contributors to many emerging and re-emerging infectious diseases. Although the pathways and extent of the environmental role are not always fully known, the disease burden and the economic impact can be significantly reduced by improved environmental management.

In recent years new diseases such as Serve Acute Repiratory Syndome (SARS), and newly resurgent familiar diseases such as tuberculosis, have caused suffering, international disruption and alarm. Frequent environmental changes are key factors. Environmental policy sometimes has a crucial role to play in controlling emerging and re-emerging diseases.

Box 1: Some definitions

Infectious diseases are caused by the invasion and unwanted growth of living organisms within the body.

Infectious disease vectors are agents that transfer pathogens from one organism to another, for instance, mosquitoes that transmit malaria parasites.

Emerging diseases are those that have recently increased in incidence or in geographic or host range (such as Lyme disease, West Nile virus, Nipah virus); that are caused by pathogens that have recently evolved (such as new strains of influenza virus, SARS, drug resistant strains of malaria); or that are newly discovered (such as Hendra virus, Hantavirus pulmonary syndrome or Ebola virus).

Re-emerging diseases are those that have been controlled in the past, but are now rapidly increasing in incidence or geographic range (such as tuberculosis). Re-emergence typically occurs because of breakdowns in public health measures for previously controlled infections, or as co-infections, such as occur with HIV.

Infectious diseases remain the leading cause of death in the world, accounting for about 15 million deaths per year – approximately 25 per cent of total global mortality (Morens and others 2004). The impact is greatest in the developing world (WHO 2003a). In Africa and South Asia, infectious diseases are the underlying cause of two thirds of all deaths, killing mostly children and young adults. Infectious diseases are also a major cause of permanent disability and poor health and well-being for tens of millions of people, hindering economic development and sustainability in many parts of the world.

The economic and social burden of diseases such as malaria is enormous (Sachs and Malaney 2002, WHO 2003a). In addition to the long-term effects, short-term epidemics of emerging or re-emerging infectious diseases, such as SARS in Hong Kong, Taiwan, and Toronto and plague in India, have each cost billions of dollars. These recent epidemics underscore the fact that we live in a worldwide community that is tightly linked, and that all of us are susceptible to the burden of infectious diseases (Morens and others 2004, Weiss and McMichael 2004).

FROM OPTIMISM TO CONCERN

The beginning of the latter half of the 20th century was marked by optimism about the conquest of infectious diseases. The discovery of antibiotics produced treatments for tuberculosis and other major infectious diseases, while insecticide use initially caused a decline in vector-borne diseases. Smallpox was eradicated and vaccines were developed for polio and other major childhood diseases. Fifty years later, due to the emergence of newly recognized infectious diseases and the re-emergence of known ones, optimism has been replaced by grave concern and, in some cases, dread (McMichael 2004, Institute of Medicine 1992 and 2001).

This growing concern in part reflects a recognition of the difficulties associated with preventing, controlling, or eradicating

Irrigation of rice fields can create excellent breeding sites for mosquitoes.

Source: Joerg Boethling/Still Pictures

Box 2: Gold and gem mining, roads, and malaria

The expansion of mining and other extractive industries can increase transmission of infectious diseases, with both local and regional impacts. The associated deforestation and road building often disrupt forest and river ecosystems, enlarging habitats for vectors, while the migration of workers increases the population at risk. For example, gem-mining areas in Sri Lanka have become epicentres of malaria because mosquitoes breed in the water that gathers in the shallow pits left behind by the gem miners (Yapabandara and others 2001). Pollution related to mining activities can impact on infection. Mercury used in small-scale gold mining, for example, has been suggested to increase people's susceptibility to the adverse impacts of malaria in Brazil, as well as polluting rivers and contaminating fish (Crompton and others 2002).

infectious diseases. Medical interventions have been unable to keep up with all infectious diseases because many disease-causing agents and vectors have developed resistance to available drugs and pesticides (Morens and others 2004, Singh and others 2004, WHO 1992). Resistance to antibiotics has been fostered by their overuse or misuse medically and in animal husbandry (Smith and others 2002, Horrigan and others 2002). In addition, the pace of vaccine and new drug development has been slower than anticipated, and the expense of new drugs has often limited their availability in developing countries. For many infectious diseases, such as malaria and dengue, vaccines are still not available.

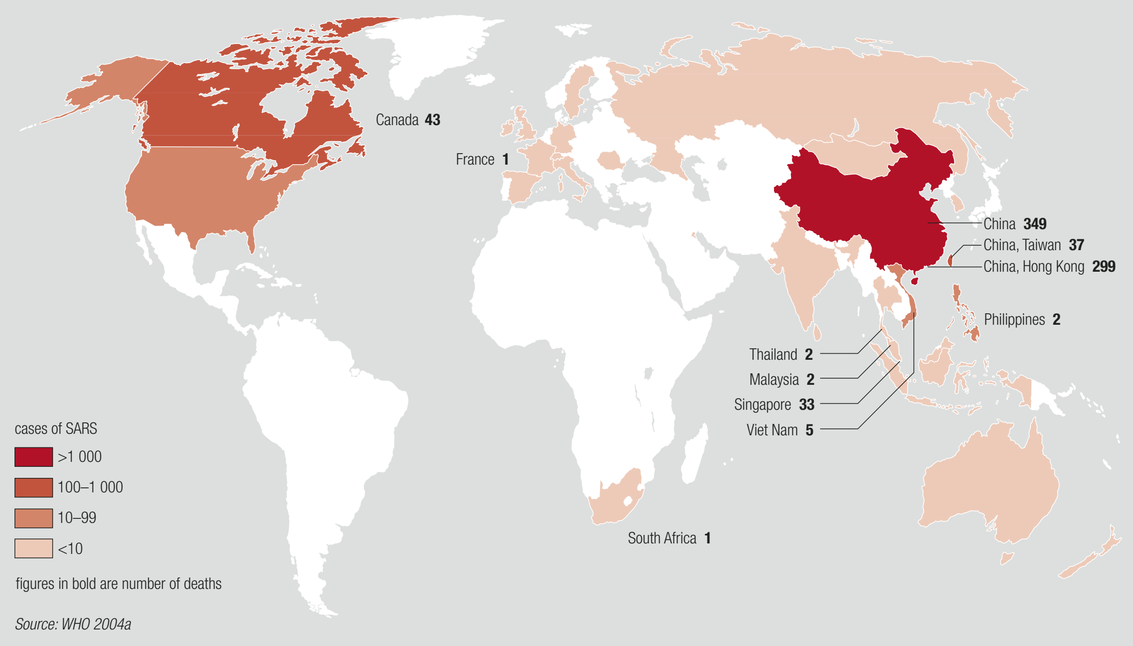
These difficulties, along with the increasing evidence that environmental change is a major player and that effective environmental management may provide more cost-effective and sustainable control measures than using drugs and pesticides, suggest a need to refocus on potentially preventable environmental factors to reverse the trend of emergent and re-emergent infectious diseases (Chivian 2002, Patz and others 2004).

DRIVING FORCES

Population growth and distribution and consumption patterns have been major driving forces of social and environmental changes in relation to land use, deforestation, agricultural practices, and water management. Research increasingly shows that many of these changes are linked to patterns of infectious disease.

Human migration, whether due to poverty, conflict, or climate-induced habitat changes, can foster the spread of emerging and re-emerging infectious diseases. Migration introduces diseases to new locations and exposes susceptible resident populations to new vector species. The devastating impact of infectious disease patterns was a common change of the initial contact of Native American groups and Pacific Islanders with Europeans. Modern transportation patterns are also having an impact. For example, the mosquito *Aedes albopictus*, which can breed in stagnant water in discarded tyres, has been globally distributed from Asia through transportation of used tyres on cargo freighters (Schaffner and others 2004, Madon and others 2002). The transfer of SARS in 2003, from South Asia to Toronto in Canada, could be traced to a single infected human who made the

Figure 1: SARS cases and deaths, 2003



figures in bold are number of deaths

Source: WHO 2004a

Aedes aegypti – the principal vector of dengue and yellow fever.

Source: David Scharf/Still Pictures

journey by commercial jet while incubating the disease (**Figure 1**). HIV/AIDS was spread widely throughout southern and central Africa by long-distance truckers, and globally by air travellers.

Unplanned rapid urbanization has resulted in inadequate housing and lack of water, sewer and waste management systems for large numbers of people in different parts of the world. When crowded human populations live in close association with large populations of mosquitoes, rodents, and other vermin, there is a dramatic increase in epidemics of diseases borne by water, food, mosquitoes and rodents, as well as in communicable diseases.

Urbanization has been the major driving force in the dramatic global resurgence of epidemic dengue and the re-emergence of its complication, dengue hemorrhagic fever (DHF) (Gubler 2004, Ko and others 1999). The global prevalence of dengue has grown dramatically in recent decades. Before 1970 only nine countries had experienced DHF epidemics: that number increased more than four-fold by 1995. It is now endemic in more than 100 countries, with South-east Asia and the western Pacific most seriously affected.

Some 2 500 million people are now at risk from dengue. In the 1950s an average of 908 DHF cases were reported to the World Health Organization (WHO) each year. This rose to an average of 514 139 cases a year for the period 1990–98. In 2001, there were more than 609 000 reported cases of dengue in the Americas alone, more than twice the number of dengue cases in 1995 (WHO 2004b).

Deforestation and agricultural practices can alter habitat availability for disease vectors.

Source: Tran Cao Bao Lond/UNEP/Still Pictures

In coastal areas, population pressure leading to coastal degradation have increased epidemics of waterborne diseases such as cholera. This may also have increased the impact of toxins resulting from algal blooms known as red tides.

ENVIRONMENTAL CHANGE AND INFECTIOUS DISEASE EMERGENCE

The various domains of environmental policy provide a framework for analyzing relationships between environmental drivers and pressures, and specific infectious diseases (**Table 1**). These linkages are further explained below.

Land

Decisions about land use can have direct and indirect impacts on infectious disease. Demand for land for agriculture and settlement has led to widespread

Discarded plastic and standing water can increase the risk of vector-borne infectious disease.

Source: Friedrich Stark/Still Pictures

Table 1: Emerging and re-emerging infectious diseases and links to environmental change

Examples of drivers of change and pressures	Examples of impacts caused by drivers and pressures	Examples of infectious disease implications	Examples of infectious diseases potentially affected
Deforestation	Ecosystem fragmentation. Destruction of natural balance leading to decrease in natural predators and changes in species dominance. Easy access by farmers/workers/hunters to new land and natural areas. Habitat disturbance.	More favourable conditions for propagation of disease vectors. Increased number of vectors in human settlements. Vector numbers and habitats increase. Increased contact with animal reservoirs and vectors.	Yellow fever, malaria, Kyasanur forest disease, Ebola and other hemorrhagic fevers, zoonotic diseases that exist normally in animals, but can infect humans.
Reforestation and expansion of housing	Housing expands into woodland/forest fringes.	Humans brought into closer contact with tick vectors and animal reservoirs (deer and rodents).	Lyme disease.
Agriculture	Monoculture destroys the natural balance, allowing propagation of vectors. Concentration of domestic animals/cattle close to humans. Land erosion and gullying – more habitat for vectors. Environmental pollution (including contamination with pesticides).	More favourable conditions for propagation of disease vectors. Vector numbers and habitats increase. Increased contact with vectors. Development of resistance by disease vectors.	Western and Venezuelan equine encephalitides, typhus.
Dam building and irrigation	More open water. More stagnant water. More fertile soil and sand beds. Environmental pollution.	Increased habitat and breeding sites for vectors and carriers.	Schistosomiasis, West Nile fever, Japanese encephalitis.
Rapid and unplanned urbanization	Ecosystem fragmentation. Destruction of natural balance. Lack of water, sewerage and waste management systems.	More sites and more favourable conditions for propagation of disease vectors. Spread of vectors and parasites. Increased contact with infected people.	Tuberculosis, dengue hemorrhagic fever, plague, Hantavirus pulmonary syndrome.
Untreated drinking water and waste water Inadequate sanitation	Settlements without clean water and sanitation. Water pollution (including accidents).	Increased contact with infection and increased mobility of infection in case of poor water management or accidents.	Leptospirosis, malaria, cholera, cryptosporidia, diarrhoeal diseases.
Industry Transport	Deteriorating air quality. Anthropogenic greenhouse gas emissions leading to global warming.	Impaired lung function. Increased mobility of infected people. Spread of diseases and vectors into high latitudes and altitudes.	(Aggravated) respiratory diseases and infections, meningitis, cholera.
Chemical use Antibiotics in livestock and livestock waste	Antibiotics in livestock products and waste.	Developing resistance in bacteria.	Hepatitis, dengue, antibiotic-resistant bacterial diarrhoeal disease.

Notes: This table is selective and illustrative. Some diseases have more than one environmental 'driver'. Many of the underlying drivers are primarily cultural, economic, demographic, and social.

deforestation and land cover change affecting wildlife habitat. These practices have resulted in an increase in zoonotic diseases (in which animals are the reservoirs of the infectious agent) in those areas where the populations of carrier animals have expanded or their contact with humans increased. Land use changes account for a majority of emerging and re-emerging infections, including major parasitic diseases such as Chagas disease, trypanosomiasis, leishmaniasis and onchocerciasis (Molyneux 1998), each of which has one or more animal reservoirs in the wild.

Habitat changes also alter the availability and reproductive capacity of vectors that transmit and sometimes also act as reservoirs of diseases. For example, some of the major vector-borne infectious diseases, including malaria, Japanese encephalitis, and dengue hemorrhagic fever, are transmitted by various species of mosquito (Gubler 2002). Opportunities for mosquito breeding in standing water are often increased by habitat and land-use change, by changes in natural water flows, by environmental degradation caused by human activities, and even by human-made containers such as discarded automobile tyres and non-biodegradable plastic (Gubler 1998). Environmental and public health management practices that decrease unnecessary standing water can often reduce the risk of vector-borne infectious disease.

Road building to open up wilderness for agriculture, mining, forestry, or other purposes can alter vector habitat, promoting the spread of vectors that favour more open areas. New roads can also lead to the migration of susceptible human populations to areas in which infectious disease pathogens and their vectors are present (**Boxes 2** and **3**).

Box 3: Bushmeat, Ebola and HIV/AIDS

Humans are susceptible to many of the same diseases that plague the great apes (chimpanzees, bonobos, gorillas and orangutans). Historically there has been little contact between people and apes, so little opportunity for diseases to transfer. But in Central Africa, the growing migration of human populations and increased access to forest habitats have allowed the trade in wild meat ('bushmeat') to flourish.

Recent analyses have linked the first human cases in Ebola outbreaks to the handling of meat from infected apes (Leroy and others 2004). The Ebola virus, discovered in 1976, is fatal in a high proportion of cases in humans and great apes. Outbreaks in Central Africa have killed hundreds of people and thousands of apes in the last few years. Disease transmission is a strong argument against the consumption of primate meat.

Retroviruses including HIV and simian foamy virus (SFV) have also been contracted this way (Wolfe 2004). HIV/AIDS is suspected to have originated from the fusion of two Simian Immunodeficiency Viruses, possibly acquired by humans through direct exposure to animal blood and secretions through hunting, butchering, or consumption of uncooked contaminated meat (Hahn and others 2000).

Ebola outbreaks, 1976–2004

Year	Country	Cases	Deaths	Fatality (%)
1976	Sudan	284	151	53
1976–77	Zaire	319	281	88
1979	Sudan	34	22	65
1994	Gabon	52	31	60
1994	Côte d'Ivoire	1	0	0
1995	Liberia	1	0	0
1995	Democratic Republic of Congo (formerly Zaire)	315	250	81
1996–97	Gabon	97	66	68
1996	South Africa	1	1	100
2000–01	Uganda	425	224	53
2001–02	Gabon	65	53	82
2001–03	Republic of Congo	237	201	85
2004	Sudan	17	7	41
Total		**1848**	**1287**	

Source: WHO 2004c

Bushmeat on sale for passing motorists, Central Africa.

Source: Martin Harvey/Still Pictures

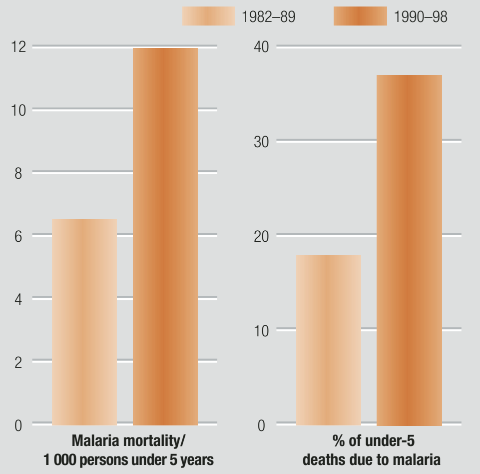
The way that land is used for agriculture can also have widely divergent effects on the habitat for infectious disease vectors, depending on the prevalence of irrigation, agroforestry, prior felling of forests and so on. For example, irrigation of rice fields will create excellent breeding sites for mosquitoes. The use of insecticides however sometimes has a greater detrimental effect on natural predators of mosquitoes than on mosquitoes themselves.

Natural habitats

Intact ecosystems can help control diseases by providing a balance of species potentially involved in the life cycle of infectious diseases, along with predators and other agents that control or limit the animal reservoirs, vectors and pathogens. Disease agents that live much of their life cycle outside the human host, such as those responsible for water- and vector-borne diseases, are highly susceptible to environmental conditions. It is these diseases for which the greatest linkages to surrounding ecology have been found.

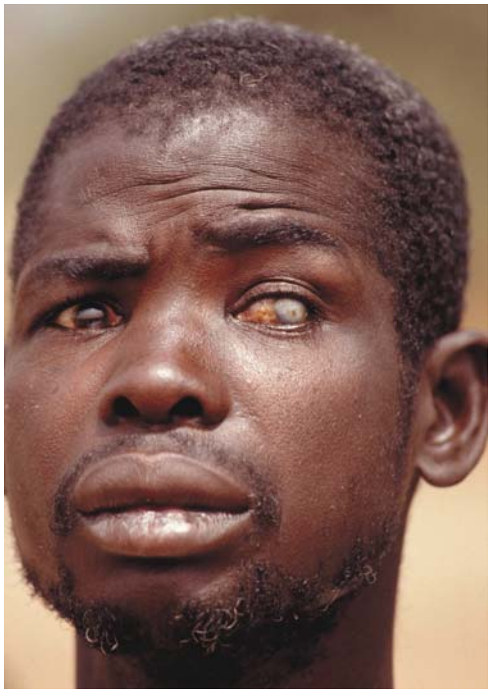
Anopheline mosquito species occupy a variety of ecological niches that can be altered by environmental changes (Keating and others 2003). For example, partial deforestation, with subsequent changes in land use and human settlement patterns, has coincided with an upsurge of malaria and its Anopheline mosquito vectors in Africa, Asia, and Latin America (Walsh and others 1993). In eastern and southern Africa, the proportion of under-five deaths due to malaria doubled between 1982–89 and 1990–98 (**Figure 2**). Climate change,

Figure 2: Malaria resurgence in eastern and southern Africa



Source: WHO 2003b

resistance to drugs, and the spread of HIV/AIDS causing depressed immune function, are also factors in the increased incidence of malaria (WHO 2003b).



The incidence of onchocerciasis (river blindness) can be affected by land use change.

Source: Mark Edwards/Still Pictures

Forest destruction can lead to a decrease or increase in onchocerciasis (river blindness, caused by the filarial worm *Onchocerca volvulus*), depending upon the impact of such factors as remaining forest cover and new stream flow regimes on the habitat of the black fly which transmits the larvae (Walsh and others 1993). On the other hand, reforestation can also take its toll. In northeastern United States it has enhanced the spread of Lyme disease (**Box 4**).

Water

Traditionally, concern about water and human health has focused on the diseases that result from inadequate or unsafe water supplies or sanitation. For example, the presence of human and animal wastes in surface waters has resulted in devastating outbreaks of cryptosporidiosis in North America and in cholera in many parts of the world (Colwell 1996, Rodo and others 2002).

However, there are many other ways in which environment-related changes in human use and management of, and contacts with, water can affect disease incidence and transmission, at every scale from the puddle in the yard to a major irrigation system. Dam construction is a driving force in infectious disease because it alters the nature of aquatic habitats and affects species survival (Patz and others 2004). The construction of large dams has caused an increased incidence of schistosomiasis (**Box 5**). By providing habitats for infectious disease vectors, irrigation has resulted in dramatic increases in morbidity and mortality due to malaria in Africa and to Japanese encephalitis in Asia.

Climate

Emissions of carbon dioxide, methane, and other greenhouse gases from land use change and industrial activities are contributing to climate change, and thus may be indirectly involved in emerging and re-emerging infectious diseases (IPCC 2000).

Changes in climate inevitably lead to changes in habitat and a resultant change in the location of vectors (Kovats and others 2003). While the net effect globally remains uncertain and somewhat controversial (Reiter 2001, Hay and others 2002, Confalonieri 2003), local changes in the risk of vector borne infectious disease are virtually certain (Patz 2002). Certain microbial organisms, such as *Neisseria meningitidis*, a common cause of meningitis, can be borne many miles on the wind in dusty conditions following exacerbated

Box 4: Reforestation, biodiversity loss, and Lyme disease

Lyme disease is a bacterial disease occurring in North America, Europe, and Asia that is transmitted by the bite of infected deer ticks. It was first named in 1977, but was recognized earlier. The major reservoir hosts for the bacteria are rodents, while deer are the major host for the tick vectors (Steere and others 2004).

Patchy reforestation of the northeastern United States led to a dramatic increase in the deer population, which in turn increased the tick population. Habitat changes also decreased rodent predators, resulting in an expansion of rodent hosts for the Lyme disease pathogen. Wet conditions in late spring and early summer were associated with an increase in Lyme disease incidence in the northeast of the country possibly by increasing tick survival and activity (McCabe and Bunnell 2004).

These environmental changes have been combined with increased human use of this habitat for homes and recreation. Because new homes are often built in wooded areas, transmission of Lyme disease near homes has become an important problem. Dutchess County, a semi-rural peri-urban county north of New York City, has one of the highest incidences of Lyme disease in the United States, with a crude mean annual incidence rate of 400 cases per 100 000 persons per year during the period 1992–2000 (Chow and others 2003). Specific strategies such as clearing leaf litter, and brush- and wood-piles in gardens can reduce deer, mouse and tick habitat thereby reducing the tick population and likelihood of disease (CDC 2004a, CDC 2004b).

The female deer tick, *Ixodes dammini*, is the vector for Lyme disease.

Source: Kent Wood/Still Pictures

Box 5: Irrigation, schistosomiasis and West Nile Virus

Snails serve as an intermediate reservoir host for schistosomiasis, and irrigation canals can provide an ideal habitat. Increasing fecundity and growth of freshwater snails are related to decreased water salinity and increased alkalinity following irrigation development along the Senegal River, and to water flow changes associated with the Aswan Dam in Egypt (Abdel-Wahab and others 1979).

Irrigation ponds, canals, and ditches can also provide larval habitat for vector mosquito species such as *Culex tarsalis*. As it bites both animals and humans, *Culex tarsalis* is a major bridge vector for enzootic diseases (diseases constantly present in animal populations) such as St. Louis encephalitis in the western United States (Mahmood and others 2004). As West Nile virus has moved into the region in the past three years, this species has emerged as the principal mosquito vector, resulting in a major epidemic in humans, and in birds and horses (Reisen and others 2004).

Schistosome snails, *Biomphalaria glabrata*, shedding schistosome larvae which burrow into people and cause schistosomiasis.

Source: Darlyne A. Murawski/Still Pictures

droughts in the Sahel (Cunin and others 2003). Cholera outbreaks are also influence by climate events such as El Niño (**Box 6**).

Chemicals

Chemical pesticides have been successful in controlling vectors responsible for infectious disease – but this has to be balanced carefully against their potential for short- and long-term adverse impacts on health and the environment. The cost-benefit issues will differ for different diseases and in different parts of the world, depending in part on the impact, incidence, and prevalence of the vector-borne disease.

Public health pesticides have played a major role in the successful control of vector-borne diseases. The Global Malaria Eradication Programme, which successfully controlled malaria and saved tens of millions of lives over much of Asia, Oceania, and the Americas, was based on indoor spraying of DDT. This and related compounds were also instrumental in the successful mosquito eradication programme in the American tropics, to control epidemics of yellow fever and dengue. Misuse of pesticides has been primarily associated with broad scale agricultural use, rather than with disease control (Horrigan and others 2002).

Box 6: Climate and cholera

The bacterial species responsible for cholera proliferate in warm waters. Copepods, tiny zooplankton that feed on algae, can serve as reservoirs for *Vibrio cholerae* and other enteric pathogens. In Bangladesh, cholera follows seasonal warming of sea surface temperature that can increase plankton blooms. El Niño and La Nina events seem to intensify the pattern of cholera incidence – cholera increases after warm events and decreases after cold events (Rodo and others 2002, Kovats and others 2003).

Significant concern also exists that a variety of chemical pollutants have an adverse impact on human resistance to infectious disease. Furthermore, the development of insect resistance to pesticides has meant that many chemical agents are no longer effective, and there is a likelihood that resistance will develop to new chemical agents. Many other chemicals, including certain flame-retardants used in electronic equipment, are suspected of disrupting the human endocrine system.

POLICY IMPLICATIONS AND CONCLUSIONS

In some parts of the world, illness and death from infectious diseases affect such a high proportion of the population that they severely threaten sustainable development. The current toll of human death and disability, as well as the social and economic disruptions caused by emerging and re-emerging infectious diseases, warrant a high priority for developing effective prevention and control measures (Sachs and Malaney 2002).

Because environmental change, in many cases, plays a major role in the emergence and re-emergence of infectious diseases, environmental policy can have a significant impact on the incidence and cost of these diseases.

Areas of potential action are very wide-ranging, covering many fields and potentially impacting the incidence of many diseases. They include protection of land, air, water, and natural habitats, and regulation of industrial chemicals and pesticides use. Effective disease prevention requires an inter-sectoral effort: environment, public health, industrial, agricultural, and urban policies need to be developed and implemented in concert. These efforts should occur in the context of existing national and international activities including those focused on global climate change and biodiversity.

Environmental ministries and agencies may have a crucial role to play in human health. Emerging and re-emerging infectious disease should be a new area of policy concern, alongside more traditional concerns of pollution, quality of the environment and nature conservation. In some countries, governments may wish to consider adding routine infectious disease considerations, including the impact of habitat changes on hosts and vectors, to environmental impact assessments and to health impact assessments.

The role of other stakeholders in preventing emerging and re-emerging infections must be enhanced by promoting inter-sectoral cooperation at every level. Because the interactions of environmental factors with infectious disease vectors and pathogens are so complex, effective understanding and response will require personnel with diverse disciplinary and cross-disciplinary knowledge. Developing, using and linking effective health and environmental monitoring systems will be crucial (Patz and others 2004). Incorporating geographic information systems into monitoring systems already shows much promise (Eisele and others 2003).

Collaborative multidisciplinary and multinational research will be needed to explore the linkages among environmental dynamics, disease vectors, pathogens, and human susceptibility. The role of the environment in emerging and re-emerging infectious diseases should be considered in future scenarios of global change – including the possibility of health benefits from greenhouse gas mitigation (Cifuentes and others 2001).

Local measures such as reduction of unnecessary standing water to prevent malaria together with worldwide efforts to ensure safe water and improved sanitation could lead to public health triumphs. But they can only be achieved by giving a high priority to preventable health problems caused by environmental conditions.

As the global SARS epidemic demonstrated, even a small number of cases of an emerging infection can cause major international social and economic disruption. In a globalizing world undergoing rapid environmental change, local actions must be combined with enhanced cooperation at global and regional levels.

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Abrupt Climate Change: Ocean Salinity Changes and Potential Impacts on Ocean Circulation

Global warming is increasing high latitude precipitation and river runoff while also melting Arctic ice-caps and glaciers, causing more freshwater to enter the oceans in northern high latitudes. The freshwater lowers ocean salinity – and since salinity is one of the key drivers of the long-distance ocean circulation that distributes the planet's heat, this could have serious consequences.

Ocean-Atmosphere-Climate dynamics

Records from Greenland ice cores (Cuffey and Clow 1997) illustrate that abrupt temperature oscillations were the norm over much of the past 100 000 years. Shifts between warm and cold climates occurred rapidly, sometimes within a decade (Alley and others 1993, Alley and others 2003). This suggests that such abrupt changes could occur again.

Over the past 8 000 years these oscillations have been absent, and the Earth has experienced several millennia of relatively stable climate. Modern human civilization developed during this period. It was and is based on permanent agriculture, which depends upon a stable climate with predictable patterns of temperature and rainfall. If abrupt change were to recur, there would be unique challenges to human societies, and to natural ecosystems which have great difficulty adapting to rapid change.

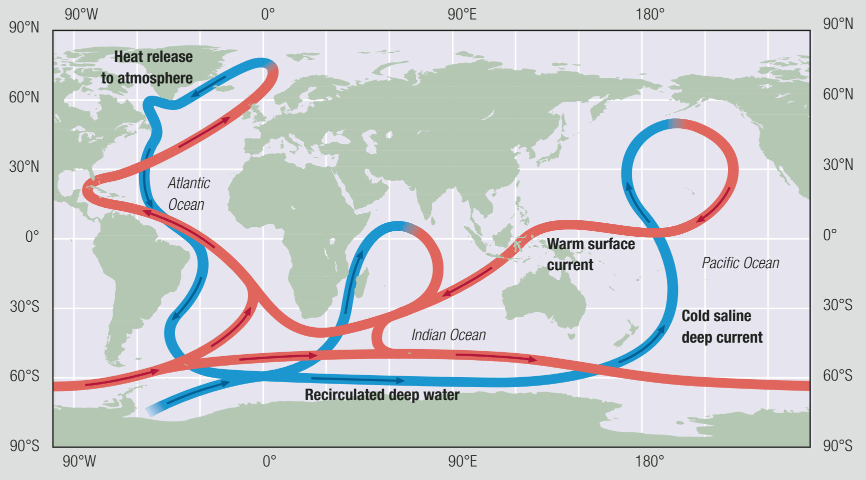
A major factor involved in the abrupt climate changes of the past appears to have been changes in the ocean circulation, which distributes heat from the equator toward the poles. This circulation is controlled in part by differences in seawater density, which is determined by the temperature and salt content of the water. The colder and saltier the water, the more dense it is, and the more readily it sinks. Flows within the oceans related to variations in temperature and salt are called the 'thermohaline circulation' ('thermo' for heat and 'haline' for salt) or the 'Conveyor' (Broecker 1995) (**Figure 1**).

As the waters of the warm Gulf Stream-North Atlantic current system flow northward, the surface waters cool and thus become denser. In some locations, the salty surface waters become dense enough to sink into the deep ocean (**Figure 2**). This sinking is called ventilation or deep convection and generally occurs in the Greenland, Iceland, Norwegian and Labrador Seas as well as in the subpolar gyre of the North Atlantic (**Figure 1**).

When the surface waters sink, they pull in additional waters and ultimately form the North Atlantic Deep Water that flows southward. In turn, this draws more warm water at the surface northward (**Figure 2**).

The northward-flowing compensating flow of warm water has a crucial climatic function for northern and western Europe and some parts of northeastern America. It carries heat from lower latitudes, losing much of this to the atmosphere as it moves northward. In doing so it makes northern and western Europe

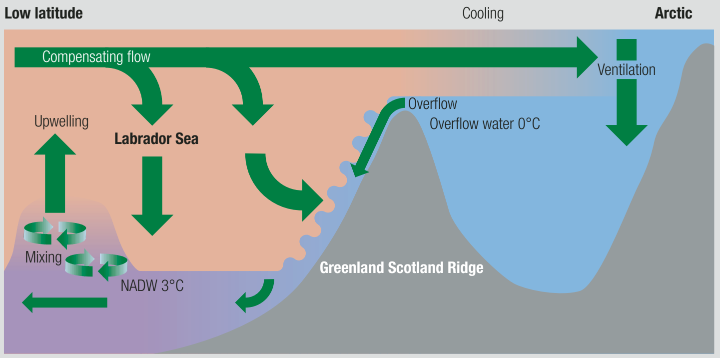
Figure 1: A schematic diagram of the global ocean Conveyor (thermohaline circulation)



Source: IPCC 2001

Red indicates warm surface currents, including the Gulf Stream which is important to warming Northern Europe. Blue indicates cold deep saline currents.

Figure 2: Vertical cross-section of Atlantic circulation



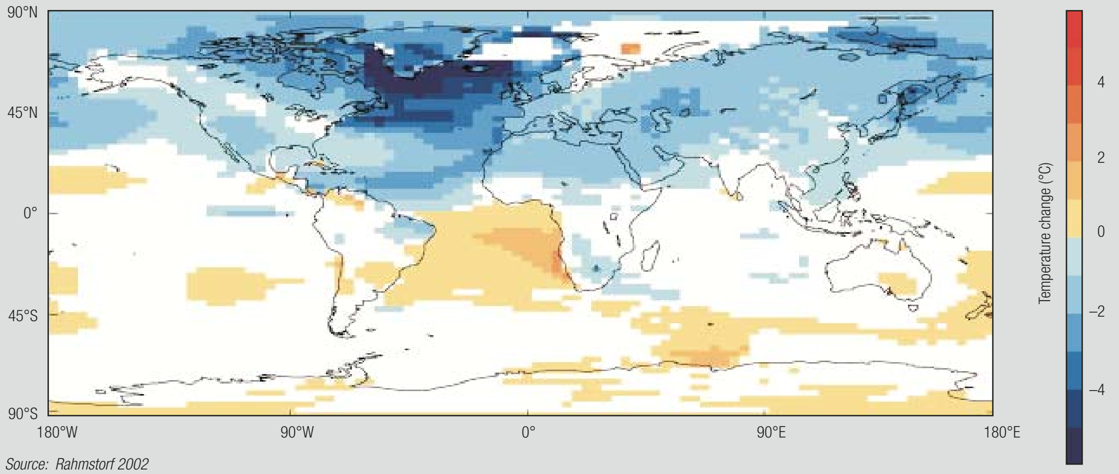
A diagram depicting the northern flow of surface waters (compensating flow), the deep sinking of dense surface waters in the Greenland, Norwegian and Labrador Seas (ventilation) and the combining of Nordic overflow waters, carried down and mixed with the deep waters of the western North Atlantic waters and Labrador Sea ventilation waters to form the southward flow of North Atlantic Deep Water (NADW). Background colours distinguish the blue Nordic Sea waters from red North Atlantic waters and purple NADW. Green arrows indicate flows.

Source: Modified from Hansen and others 2004 warmer in winter than the west coast of North America at similar latitudes.

The sinking that drives the global thermohaline circulation depends critically on the water being sufficiently cold and salty. Anything that makes the water less cold and less salty can jeopardize the circulation, with potentially serious impacts.

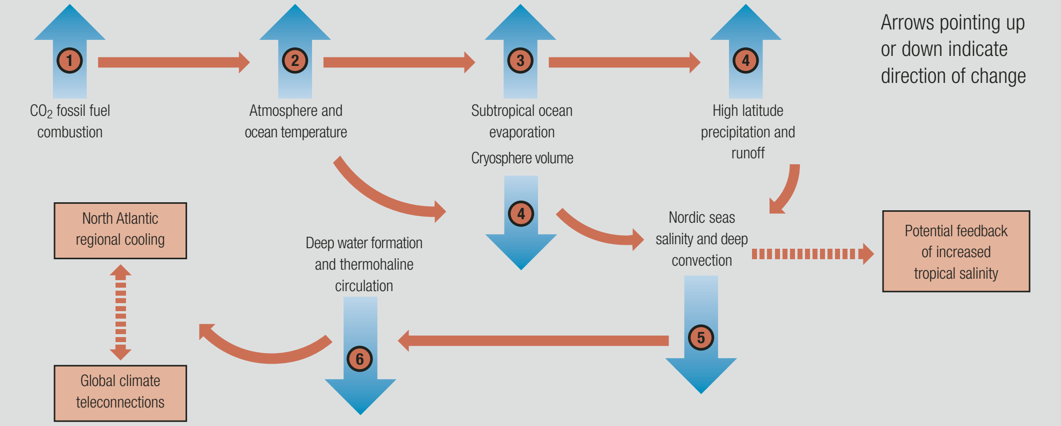
Observations over recent decades suggest that changes in the factors that govern this circulation are occurring, possibly as a result of human activities. This raises concerns about possible abrupt climate changes in the future.

Figure 3: Model estimates of air temperature changes resulting from a shutdown of the North Atlantic Conveyor



Source: Rahmstorf 2002

Figure 4: A possible sequence of events leading to alterations in the North Atlantic thermohaline circulation



Source: Bruce Peterson, Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA, US

Six steps to abrupt climate change

Theory had already predicted that such changes were possible. In the 1980s, it was suggested that climate warming could add enough freshwater to key places in the oceans to slow or even shut down the thermohaline circulation, leading to reorganization of ocean and atmospheric circulation patterns (Broecker 1987, Broecker and others 1985). Climate model results (Manabe and Stouffer 1988, Rahmstorf 1994) soon lent further support to this theory, and projected substantial cooling in the northern hemisphere, especially in the North Atlantic region, if a shutdown occurred (**Figure 3**) (Rahmstorf 2002).

Recent records suggest that the changes predicted by theory and modelling may be actually under way. Measurements of evaporation, precipitation, runoff, ocean salinity, and ocean circulation show these factors changing in ways that may reduce the density of North Atlantic subpolar waters. We may now be observing the early stages of processes that could lead to changes in ocean circulation (Curry and others 1997, Dickson and others 2002, Hansen and others 2001).

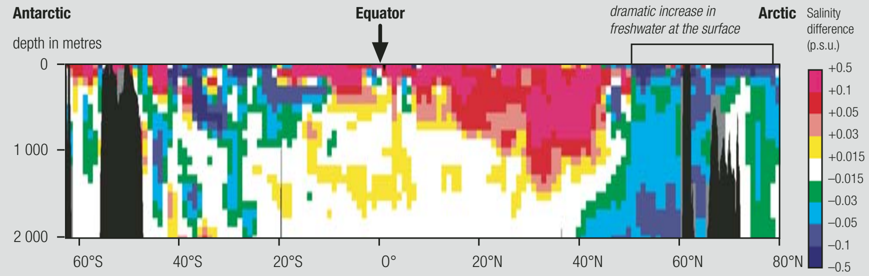
The following six steps (**Figure 4**) lay out one possible sequence of events by which human activities could lead to abrupt climate change.

Step 1: Higher carbon dioxide (CO_2) emissions increase atmospheric CO_2 concentrations.
The burning of fossil fuels (coal, oil and natural gas) and land-use changes have already created a large increase in the concentration of CO_2 in the atmosphere. CO_2 concentrations have increased by about 35 per cent since the start of the industrial revolution to the current level of 379 parts per million by volume (ppmv) (CDIAC 2004). Concentrations are projected to rise much more if emissions are not sharply reduced (IPCC 2001).

Step 2: This increases global temperatures.
CO_2 and other greenhouse gases in the Earth's atmosphere cause an increase in the air temperature near the surface of the Earth. Global average surface air temperature has already risen by 0.6° C over the past 100 years (IPCC 2001). It is projected to rise by another 1.4 to 5.8° C over the next 100 years, according to the range of climate models evaluated by the Intergovernmental Panel on Climate Change (IPCC 2001).

Step 3: Ocean evaporation and surface salinity increase in subtropical latitudes.
The atmospheric warming increases the evaporation of water from the surface of the subtropical oceans, increasing their salinity. A 5–10 per cent increase in evaporation has already been observed in the subtropical Atlantic Ocean over the past 40 years, equivalent to 5–10 cm of surface ocean water

Figure 5: Changes in Atlantic Ocean salinity distribution from the 1960s to the 1990s



Units are salinity change in parts per thousand (ppt) on log scale as indicated. Black areas are sea bottom features such as the ridges between the Arctic Ocean and North Atlantic near the north end of the transect.

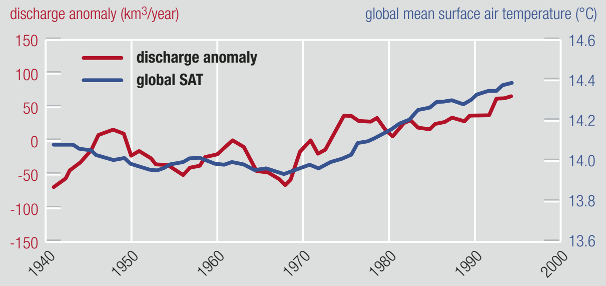
Source: Curry and others 1997

each year (Curry and others 1997). **Figure 5** shows the resulting increase in surface water salinity in the subtropical Atlantic as calculated and interpolated from direct measurements of salinity. Similar trends in salinity have been observed in the Pacific and Indian Oceans (Wong and others 1999).

Step 4: Precipitation, runoff and glacial melt increase in northern high latitudes, adding excess freshwater to the ocean surface layers in these regions.

The increased moisture evaporated from the subtropical oceans condenses in the atmosphere at higher latitudes, leading to increased precipitation. There has in fact been an increase in precipitation of 6–12 per cent in the northern high latitudes over the last century (IPCC 2001), resulting in increased freshwater runoff from rivers in Russia. The most dramatic increases have occurred in recent decades (Peterson and others 2002) (**Figure 6**). Increased melting from the Greenland Ice Sheet and other arctic glaciers has also added more freshwater to the Arctic Ocean over the past 40 years (Dyurgerov and Carter 2004). By comparison, the construction of dams and the melting of permafrost have had minor impacts on the long-term pattern of change in river discharge (McClelland and others 2004).

Figure 6: Eurasian river discharge anomaly, and global surface air temperature (SAT) expressed as 10 year running means for 1936–99



Source: Peterson and others 2002

Melting sea ice adds a further source of additional freshwater, because sea ice contains little salt as it rejects most of its salt as it forms. Sea ice extent has declined by 2–3 per cent per decade since 1978 (Comiso and Parkinson 2004). The arctic sea ice is not just shrinking in area but also thinning, leading to predictions that the Arctic Ocean may be free of ice in summer by the end of this century (Yu and others 2004, Laxon and others 2003). These warming-induced increases in precipitation, runoff, glacial melt and sea ice melt could potentially reduce the salinity of surface waters in the Arctic and North Atlantic Oceans.

Step 5: Surface ocean salinity decreases at key locations of deep convection in the North Atlantic.

The Conveyor described above depends on delicately balanced processes. If surface waters in the Greenland, Iceland, Norwegian and Labrador Seas and the subpolar gyre of the North Atlantic are made less salty by an increase in freshwater input due to rising precipitation and runoff, or if temperatures are not sufficiently cold, these waters will not sink as usual. Instead, they will remain on top of the denser saltier waters below, capping them in much the same way as a layer of oil rests above a layer of water. This would stop the initiation of the deep convection that links the surface and bottom portions of the Conveyor.

There is evidence that freshening has been occurring for several decades in the North Atlantic and adjacent seas (**Figures 5** and **7**). For example, the volume of dense deep water (water of temperature <0.5° C, and of density greater than 1 028 kg/m³) in the Norwegian Sea has been decreasing for the last 50 years. This has led to a decline in the overflow of this deep water (a precursor to North Atlantic Deep Water) via the Faroe Bank Channel into the North Atlantic (Hansen and others 2001) (see **Figures 2** and **7**).

Similarly, the stock of dense deep waters in the Greenland Sea has declined during the period from the 1970s to the 1990s, and a cap of less saline water has accumulated (Curry and others 1997, Curry and Mauritzen *in print*). The density gradient that drives the overflow across the Denmark Strait Sill has decreased by about 10 per cent, suggesting that the overflow of this second precursor to North Atlantic Deep Water (NADW) may also have declined.

These trends of declining salinity and density in the Nordic Seas are supported by evidence for four decades of salinity decline in deep waters in the North Atlantic and Labrador Sea at additional locations downstream of these overflows (Dickson and others 2002) (**Figure 7**).

Step 6: There is a slowing or stopping in the ocean circulation that distributes the planet's heat, potentially causing abrupt climate change.

The final step of the process would occur if the sinking of surface water and southward flow of the deep water part of the Conveyor slowed or stopped. If this happened, the warm subtropical waters would not flow northward as they do now.

Direct measurements of a decline in the northward transport of tropical Atlantic Ocean waters have not yet been made, although the multi-decadal slowdown in the overflows of dense deep waters from the Norwegian and Greenland Seas (Hansen and others 2004) suggest that some slowing of the northern-most segment might already be occurring. There is also evidence that some of the freshwater is being carried down and mixed with the deep waters of the western North Atlantic and Labrador Sea (Dickson and others 2002), so while the Conveyor is still operating, it is now carrying more freshwater to depth than in previous decades (**Figures 5** and **7**).

Perspectives

Has the modest 0.6° C global warming of the past century left such a widespread imprint on the global hydrological cycle that the first five steps leading to a potential shutdown of the thermohaline circulation are already measurable?

The trends in the data suggest that the changes in subtropical evaporation, high latitude precipitation and runoff, and ocean salinity predicted by General Circulation Models (GCMs) for greenhouse warming scenarios may be under way (Curry and others 1979, Hansen and others 2004, Manabe and Stouffer 1994). We must learn how to better distinguish natural changes from those caused by human activities such as fossil fuel burning, before we can definitely attribute the changes in the hydrological cycle and ocean salinity to global warming. Natural climate variability, such as natural shifts in atmospheric circulation patterns, may be responsible for some of the changes (Dickson and others 2002).

The changes observed thus far have not been large enough to greatly impact the ocean Conveyor circulation. However, a further projected warming of 1.4 to 5.8° C during the remainder of this century (IPCC 2001) would have a larger impact. The chain of events – from the increase in low latitude evaporation; to increasing high latitude precipitation, runoff and glacier melt; to the reduction in high latitude surface ocean salinity; to declining deep convection and slowing of Nordic Seas overflows – are converging to suggest that the North Atlantic thermohaline circulation may be moving in the direction of a significant weakening, or a possible collapse.

Most GCMs project that the thermohaline circulation would be slowed as a result of several degrees of global warming during this century (IPCC 2001). However, most paleo evidence for abrupt changes comes from *glacial* climate regimes. In contrast we now have a *warm* climate becoming even warmer. We do not know if there is a threshold beyond which the Conveyor would inevitably shut down under contemporary warm climate conditions.

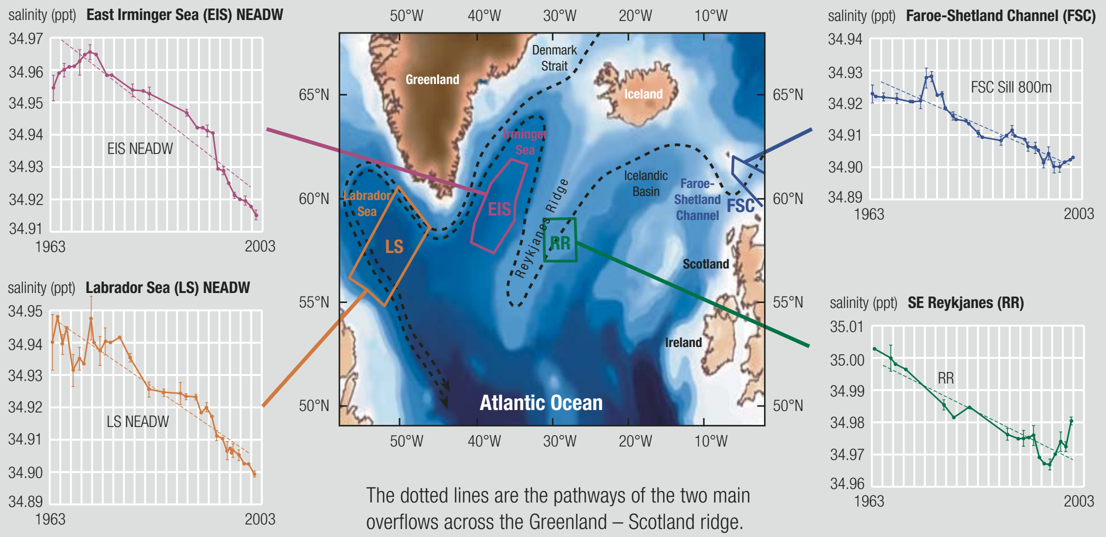
Several model studies of greenhouse warming suggest that the North Atlantic thermohaline circulation might collapse at CO_2 levels of roughly 800 to 1 000 ppm and temperature increases of 4 to 6° C (Manabe and Stouffer 1994, Schmittner and Stocker 1999, Rahmstorf and Ganopolski 1999). These are within the upper bounds of the IPCC 2001 projections for the end of this century, but may not be reached. Most of the greenhouse warming model runs performed for the IPCC Third Assessment exhibited a substantial decline in the overturning circulation by 2100 but not a complete shutdown of the Conveyor.

However, the models do not include the melting of the Greenland ice cap and arctic glaciers and therefore underestimate the freshwater forcing. Since the CO_2 and temperature projections attain maximum values *after* 2100, the model simulations are most likely to show that the largest impacts on the thermohaline circulation will occur after that date. Experiments with models also indicate that the likelihood of thermohaline circulation collapse is greater at higher rates of CO_2 release to the atmosphere (Stocker and Schmittner 1997). A slower release of the same amount of CO_2 would be less likely to cause a collapse.

While observations suggest that five of the six steps described above may be already underway, it is possible that processes that are not currently understood or accounted for in all models could alter the course of the sixth stage in unpredictable ways. Such processes might decrease the severity of the changes that might occur – or they might increase it. For example, as salty water from the subtropics moves northward, increased salinity (created by increased subtropical evaporation under global warming) may offset the freshening from high latitude precipitation and melting, thereby stabilizing the Conveyor (Latif and others 2000).

If a collapse were to occur, disruption of the Conveyor circulation might begin erratically, leading to unpredictable climatic conditions as the circulation weakened (Knutti and Stocker 2001). Alternatively, a shutdown might occur abruptly with little warning. A shutdown could lead to a regional cooling of from 2 to 5° C concentrated in the North Atlantic, including Greenland, Iceland, the British Isles, and Northern Europe (**Figure 3**), with major effects on ecological conditions both in oceans and on land. If a shutdown were to occur relatively soon, then there would be a big temperature drop. However, if the region were already warmer due to global climate change, the immediate temperature change relative to current climate conditions would be less. But even in the

Figure 7: Declining salinity levels in key areas of the North Atlantic over the last four decades



Source: Modified from Dickson and others 2002

The dotted lines are the pathways of the two main overflows across the Greenland – Scotland ridge.
NEADW = North East Atlantic Deep Water.

latter case, over time the CO_2 peak would go down as fossil fuel supplies were depleted or there was a major switch to alternative energy sources. As the CO_2 concentration dropped, the Earth's temperature would cool and, as long as the thermohaline circulation remained shut down, this region would become colder (Rahmstorf and Ganopolski 1999).

If a collapse of the Conveyor circulation were to occur, it is not clear how long it might take to restart. Evidence from ice cores and modelling suggests that it might require hundreds or thousands of years (Rahmstorf and Ganopolski 1999). In the interim, the atmospheric and ocean currents that redistribute heat from the equator toward the poles would reorganize. Prediction of the new pattern of currents is a topic of current research.

Global Ramifications

While the most apparent impact of a slowdown or shutdown in the Conveyor circulation is projected to be a climatic cooling in the North Atlantic region, more widespread impacts of a thermohaline shutdown can be illustrated from modeling studies such as the warming in the southern hemisphere (**Figure 3**).

Correlations between climate changes in the North Atlantic and in distant regions have been found in the paleo records. These distant linkages between climate conditions in one location with conditions in remote regions are termed teleconnections. For example, the strength of the Arabian Sea monsoon correlates with changes in North Atlantic climate (Schulz and others 1998). Likewise, shifts in climate and vegetation of the South American tropics correlate closely with climatic events recorded in the Greenland ice core (Hughen and others 2004). It appears that either the Conveyor circulation may have impacts far beyond the North Atlantic region or that the distant events may have a common cause. However, the teleconnections that operated during the colder glacial periods may have depended on sea ice cover in the North Atlantic whereas sea ice will not be present under contemporary warm climate conditions. Thus these teleconnections may be weaker or absent.

Slowing the thermohaline circulation would have other global effects. Deep water formation is one mechanism for carrying anthropogenic carbon dioxide down into the deep ocean. Slowing of the circulation might allow carbon dioxide in the atmosphere to build up more rapidly, possibly leading to more intense global warming (Sabine and others 2004).

CONCLUSIONS

Given the current range of uncertainties it is wise to consider model projections as indications of what *might* happen rather than predictions of what *will* happen. Obtaining a clearer outlook will require improved understanding of ocean physics, improved climate simulations, and a more precise estimate of future warming. The global freshwater cycle and ocean circulation will require close monitoring.

The scientific evidence reviewed here suggests that minimizing the buildup of CO_2 in the atmosphere would lower the projected temperature increase and therefore minimize the acceleration of the hydrological cycle. The result would be a lower probability of forcing a reorganization of the North Atlantic thermohaline circulation – and a better chance of maintaining a stable climate in the North Atlantic region and elsewhere.

The actions required to minimize the probability of abrupt climate change are the same as those needed to allow successful adaptation of natural and managed systems to global warming: that is, to reduce the rate of increase and the overall intensity of greenhouse forcing by reducing our output of greenhouse gases.

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