CLIMATE CHANGE, OCEANS, AND HUMAN HEALTH

BY JONATHAN A. PATZ,
SARAH H. OLSON, AND
AMBER L. GRAY

Current climate changes are largely associated with the accumulation of anthropogenic CO_2 in the atmosphere. Fossil-fuel burning, which currently releases about 7 billion tonnes of carbon to the atmosphere each year, contributes roughly 70 percent of the anthropogenic CO_2 emissions, while much of the rest is attributed to deforestation (Raven and Falkowski, 1999). Only about half of the anthropogenic CO_2 released to the atmosphere is absorbed by the oceans and continental vegetation. As a result, atmospheric CO_2 concentrations have increased by roughly 100 ppmv (parts per million by volume) during the last two centuries.

Due to this rapid and significant rise in atmospheric CO_2 concentrations, the Intergovernmental Panel on Climate Change (IPCC) predicts that average global temperatures will increase between 1.8°C and 5.8°C over the next century, and sea level will rise between 9 and 88 centimeters (IPCC, 2001), with midrange estimates of 3°C global mean warming and 45 cm sea-level rise, respectively. Increased variability in the hydrologic cycle (i.e., more floods and droughts) is expected to accompany these global-warming trends. The rate of change in climate is faster now than in any period in the last thousand years. And while industrialized countries are most responsible for causing global warming, it is the low-income countries with little capacity to adapt that are the most vulnerable (Patz et al., 2005).

Low-lying coastal areas and small island nations are especially at risk from sea-level rise, storms, and microbiological threats in the ocean. In general, vulnerability to climate impacts is a function of societal characteristics in combination with climate, geographic, and other phenomena. The extensive Ganges River Delta is an example of such an at-risk area.

Image acquired by Landsat 7's Enhanced Thematic Mapper plus (ETM+) on February 28, 2000. Image provided by the USGS EROS Data Center Satellite Systems Branch.

Evidence is accumulating that such changes in the broad-scale climate system may already be affecting human health outcomes sensitive to climate. For example, the World Health Organization (WHO) estimates that the warming that has already occurred in the past 30 years is responsible for over 150,000 deaths annually due to increasing rates of mortality and morbidity from extreme heat, cold, drought or storms; significant changes in air and water quality; and changes in the ecology of a wide range of microbial diseases (Campbell-Lendrum et al., 2004). Many of these deaths are occurring in low-lying coastal areas and small island nations, which are especially at risk from sea-level rise, storms, and microbiological threats in the ocean. *In general, vulnerability to climate impacts is a function of societal characteristics in combination with climate, geographic, and other phenomena.*

SEA-LEVEL RISE

As noted above, the IPCC projections indicate that the sea level will rise by an additional 11 to 88 cm by the year 2100 (Houghton et al., 1996). Thermal expansion of the ocean is expected to account for roughly half of this increase; most of the remainder will result from the melting of glaciers and ice caps, both secondary to global warming. This sea-level rise could affect human health through coastal flooding and erosion, saltwater intrusion into coastal freshwater aquifers, damage to coral reefs and coastal fisheries, and forced human population displacement. Low-lying coastal and delta regions (such as coastal China, Bangladesh, and Egypt), especially those that are densely populated, and low-lying small island states (such as coral-reef atolls throughout Polynesia) are at elevated risk (Figure 1) (McCarthy et al., 2001).

A large proportion of the world's human population lives close to coastlines where increasing trends in coastal settlement continue (see Bowen et al., this issue). The number of people who live more-or-less in harm's way as a result of such events is projected to increase from 75 million to roughly 200 million if sea level rises by 40 cm during the 21st century (McCarthy et al., 2001). For example, according to one study, a one-meter sea-level rise would inundate low-lying areas, affecting 18.6 million people in China, 13.0 million in Bangladesh, 3.5 million in Egypt, and 3.3 million in Indonesia (Nicholls and Leatherman, 1995). The

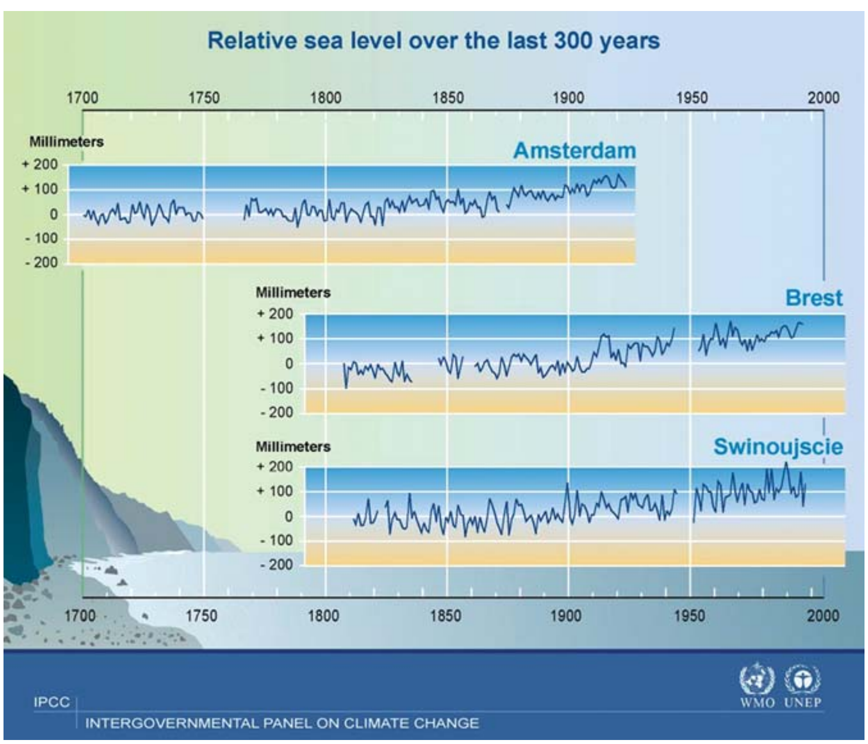

Figure 1. Relative sea-level rise over the last 300 years. Rates vary depending on local land subsidence or uplift. Global average sea-level rise has been approximately 1–2 cm per decade. Source: IPCC (2001).

Jonathan A. Patz *(patz@wisc.edu) is Associate Professor of Environmental and Population Health Studies, Center for Sustainability and the Global Environment (SAGE), Nelson Institute for Environmental Studies and Department of Population Health Sciences, University of Wisconsin, Madison, WI, USA.* **Sarah H. Olson** *is Ph.D. Candidate, Center for Sustainability and the Global Environment (SAGE), Nelson Institute for Environmental Studies, University of Wisconsin, Madison, WI, USA.* **Amber L. Gray** *is an undergraduate at the University of Wisconsin, Madison, WI, USA.*

number of people at risk from flooding by coastal storm surges is projected to increase from the current 75 million to 200 million in a modeled scenario of midrange climate changes, in which a rise in sea level of 40 cm is envisaged by the 2080s (McCarthy et al., 2001).

Salination of coastal freshwater aquifers and disruption of storm-water drainage and sewage disposal, with or without flooding, could force coastal communities to migrate (Myers and Kent, 1995). Refugees suffer substantial health burdens, overcrowding, lack of shelter, and competition for resources. In fact, increased global conflict may be one of the worst results emerging from such forced population migration (Patz and Kovats, 2002).

STORMS

Floods, droughts, and extreme storms have claimed millions of lives during the past 20 years, have adversely affected the lives of many more, and have caused billions of dollars in property damage (Noji, 1997). On average, disasters killed 123,000 people worldwide each year between 1972 and 1996. Africa suffers the highest rate of disaster-related deaths (Loretti and Tegegn, 1996), although 80 percent of people affected by disasters are in Asia.

For every one person killed in a disaster, an estimated 1,000 people are affected (International Federation of Red Cross and Red Crescent Societies [IFRC], 1998), either physically or through loss of property or livelihood. Furthermore, mental disorders (such as posttraumatic stress disorder) may substantially affect overall population wellbeing, depending upon the unexpectedness of the impact, the intensity of the experience, the degree of personal and community disruption, and long-term exposure to the visual signs of the disaster (Green, 1982).

Population concentration in high-risk areas (such as floodplains and coastal zones) increases vulnerability. Also, degradation of the local environment can contribute significantly to vulnerability (Diaz and Pulwarty, 1997). For example, worsening drought conditions in arid regions can have ramifications in the widespread (even trans-oceanic) transport of airborne dust (see case study by Prospero, this issue). As another example, Hurricane Mitch, the most deadly hurricane to strike the Western Hemisphere in the last two centuries, caused 11,000 deaths in 1998 with thousands of others still missing in Central America. Many fatalities associated with Hurricane Mitch occurred far inland as a result of mudslides in deforested areas (National Climatic Data Center, 1999).

Hurricane formation requires sea surface temperatures (SST) above 26°C (Gray, 1979; Trenberth, 2005; Webster et al., 2005; also see Keim, this issue; case study by Miller et al., this issue). This condition exists during the summer months in the Atlantic Ocean between 5°N and 25°N, and in the North Pacific, Indian, and Southwest Pacific Oceans between latitudes 5° and 20° (Webster et al., 2005). Knutson et al. (1998) found that a sea surface warming of slightly over 2°C would intensify hurricane wind speeds by 3 to 7 meters per second (or 5 to 12 percent), although predicting the number of hurricanes that will make landfall is currently not possible.

Records indicate SSTs have steadily increased over the last 100 years, and more sharply over the last 35 years. The highest average SST on record is between 1995–2004 (Trenberth, 2005). During the first half of this period, the overall hurricane activity in the North Atlantic Ocean doubled and the Caribbean Sea experienced a five-fold increase (Goldenberg et al., 2001). SST is strongly correlated with hurricane intensity and destructiveness (Figure 2) (Emanuel, 2005). Simulation models indicate future trends towards intensified hurricane seasons (Knutson and Tuleya, 2004).

Much of the variability in SST is driven by the magnitude of local vertical wind shear and the effects of the El Niño Southern Oscillation (ENSO) (Goldenberg et al., 2001). ENSO refers to natural year-to-year variations in sea-surface temperatures, surface air pressure, rainfall, and atmospheric circulation across the equatorial Pacific Ocean and beyond. This cycle provides a model for observing climate-related changes in many ecosystems. The El Niño phase of the ENSO cycle corresponds to a slackening of the Trade Wind system and a reduction in atmospheric pressure differentials across the equatorial Pacific. In recent years, the only normal regional storm activity (as measured by the Accumulated Cyclone Energy index) occurred during El Niño events, which suppress activity in the North Atlantic Ocean (Trenberth, 2005).

OCEANS, ENSO, AND INFECTIOUS DISEASE EPIDEMICS

Ocean temperatures associated with ENSO can strongly influence the resurgence of major infectious diseases on land. For example, ENSO-driven climate variability has been linked to large epi-

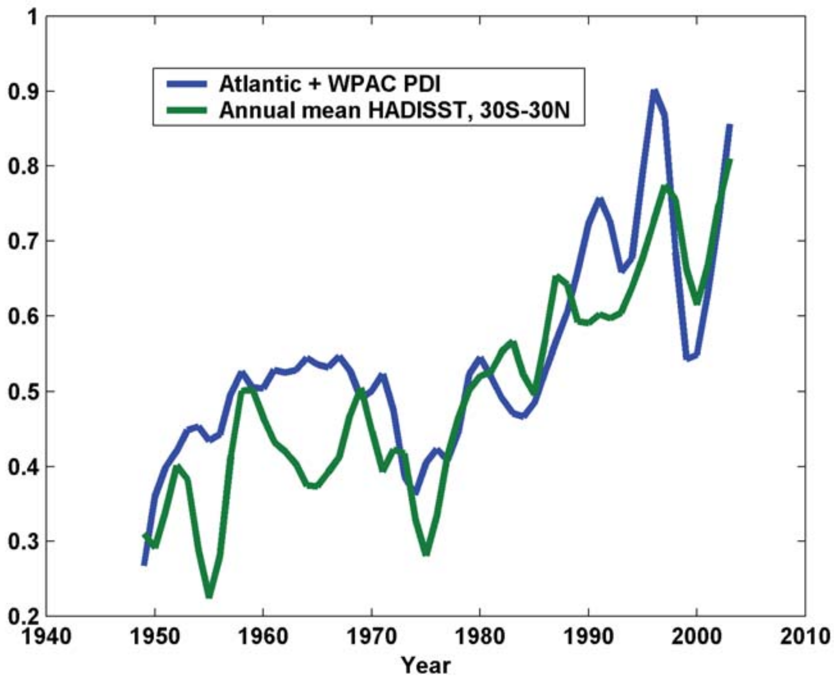

Figure 2. Annually accumulated power dissipation index (PDI) for the western North Pacific and North Atlantic, compared to annually averaged sea surface temperature (Hadley Centre SST or HadISST). Both time series have been transformed to facilitate comparison. Source: Emanuel (2005).

demics of malaria on the Indian subcontinent and South America (Bouma and van der Kaay, 1996; Bouma and Dye, 1997). In East Africa, Rift Valley Fever epidemics (a mosquito-borne viral disease) have coincided with unusually high rainfall associated with ENSO-related Pacific and Indian Ocean SST anomalies (Linthicum et al., 1999). Following the strong ENSO of 1997–1998, rainfall in the Rift Valley increased more than 50-fold and a major Rift Valley Fever epidemic ensued. These heavy rains resulted from the convergence of the strong ENSO with an unusually warm phase of the Indian Ocean, illustrating an important health-related link to sea-surface conditions. In fact, further analysis showed that over three quarters of the Rift Valley Fever outbreaks between 1950 and 1988 occurred during warm ENSO event periods (Anyamba et al., 2001).

TEMPERATURE AND DISSOLVED CO_2 THREATS TO FISHERIES AND PROTEIN MALNUTRITION

Malnutrition remains one of the largest health crises worldwide; according to the WHO, approximately 800 million people are undernourished (WHO, 2002). Droughts and other climate extremes have direct impacts on food crops and can indirectly influence land-based food supply by altering the ecology of plant pathogens. Also, climate effects on fisheries threaten coastal and island populations that rely on fish as the main source of protein.

Worldwide, fish provides 16 percent of the animal protein consumed by people (see Dewailly and Knap, this issue). However, fish represent a higher proportion of protein in some regions (e.g., 26 percent in Asia). Global extinctions of fish are not likely to occur from climate change alone. However, worrisome evidence is emerging on the adverse effect of warmer temperatures on the world's fisheries. The recent slowing of the North Atlantic Gulf Stream may affect the abundance and seasonality of plankton that are a major source of food for many fish larvae (Pauly and Alder, 2005). Declining larval fish populations will affect the capacity of overexploited fish stocks to recover.

Climate change may also disrupt fisheries as a result of both warming and changes in ocean current patterns, including freshwater input (Pauly and Alder, 2005). The capacity of fish to adapt to such changes is unknown, but the oceanic alterations projected from most global climate scenarios fall beyond most parameter ranges observed under natural marine regimes.

Finally, concern has arisen regarding the lowering of the pH of oceans (i.e., increasing acidity) from the CO_2 sequestration. From a human health perspective, however, the impact of rising ocean acidity on marine life is largely unknown. Legitimate concern exists over further stress on fisheries from anticipated accelerated damage to corals and hard-shelled organisms because acidification decreases the availability of calcium carbonate from the water.

Coupled with coral-reef bleaching from warmer temperatures, fisheries will likely be stressed further. Some models predict that a mean sea surface warming of only 1°C could cause the global collapse of coral-reef ecosystems (Pew Oceans Commission, 2003).

MARINE MICROBIOLOGICAL EFFECTS

Warm water and increased nitrogen levels can favor blooms of certain marine algae, particularly cyanobacteria (blue green algae), dinoflagellates, and diatoms, which can release toxins into the marine environment. These blooms—also known as "red tides" or "harmful algal blooms (HABs)"—can cause acute and possibly chronic paralytic, diarrheic, neurologic, and amnesiac poisoning in humans through consumption of contaminated seafood and aerosol exposures, as well as extensive die-offs of fish and of marine mammals and birds that depend on the marine food web (Figure 3) (Tester, 1994; Glibert et al., 2005; Backer and McGillicuddy, this issue; case study by Abraham and Baden, this issue). Over the past three decades, the frequency and global distribution of toxic algal incidents appear to have increased, and more human intoxication from algal sources has occurred (Van Dolah, 2000). The present variability and occurrence of harmful algal blooms (HABS) (within the last 60-year record) is unrivaled in the past (Mudie et al., 2002).

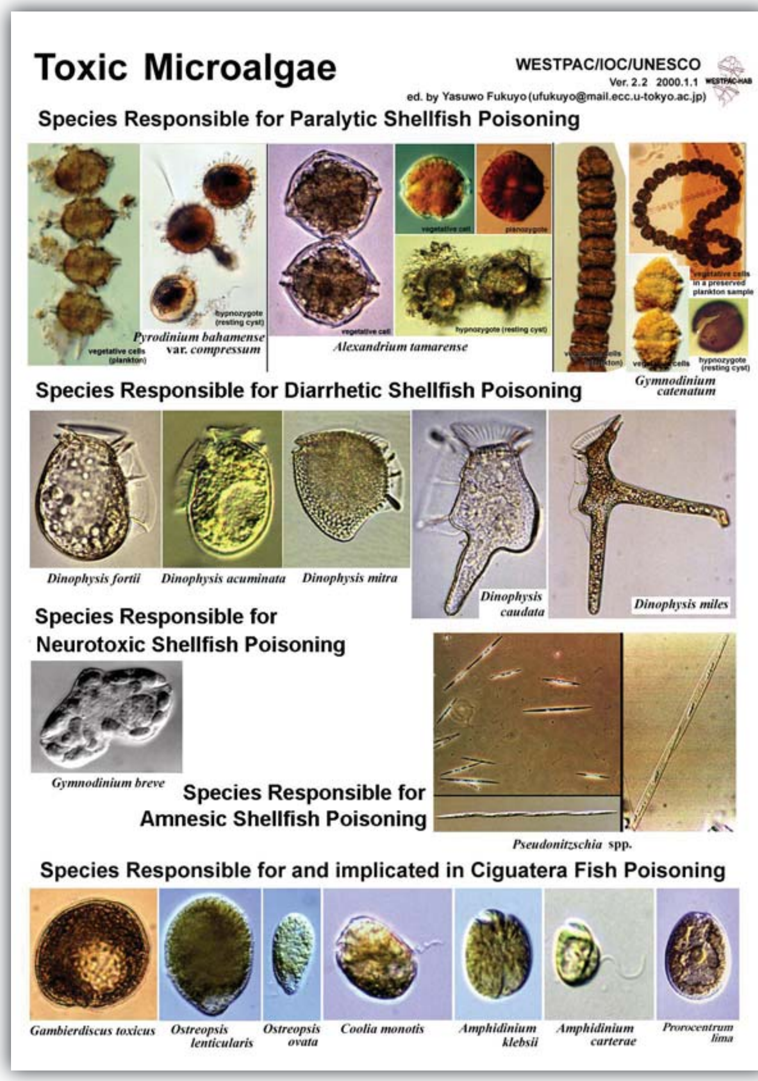

Figure 3. Toxin-producing microalgae. Source: http://dinos.anesc.u-tokyo.ac.jp/Jpeg/index.htm.

Recent studies have linked SST, upwelling events, and certain HABs (Sacau-Cuadrado et al., 2003). Wind force has also been a related variable in HABs (Sierra-Beltran et al., 2004). During the 1987 El Niño, a bloom of the dinoflagellate *Gymnodinium breve* (now known as *Karenia brevis*), previously confined to the Gulf of Mexico, extended northward after warm Gulf Stream water reached far up the east coast, resulting in human neurological shellfish poisoning (NSP) and substantial fish kills in North Carolina (Tester et al., 1991). Similarly that year, an outbreak of amnesic shellfish poisoning (ASP) occurred on Prince Edward Island when warm eddies of the Gulf Stream neared the shore, and heavy rains increased nutrient-rich runoff, resulting in a bloom of the causative diatom, *Pseudonitzchia* (Hallegraeff, 1993).

Modeling in the Netherlands shows that by 2100, a 4°C increase in summer temperatures in combination with water-column stratification would double growth rates of several species of HABs in the North Sea (Peperzak, 2005). Biotoxin-associated human diseases seen with warmer waters also include ciguatera fish poisoning, which could extend its range to higher latitudes. An association has been found between ciguatera (fish poisoning) and SST in some Pacific Islands (Hales et al., 1999).

Vibrio species of bacteria also proliferate in warm marine waters (see Dufour and Wymer, this issue). Other marine bacteria are capable of inhibiting the growth of *V. cholerae*, but warm temperatures reduce this process, allowing *V. cholerae* proliferation (Long et al., 2005). Also, copepods (or zooplankton), which feed on algae, can serve as reservoirs for *V. cholerae* and other enteric pathogens. Therefore, in Bangladesh, cholera follows seasonal warming of SST that can enhance plankton blooms, which in turn lead to blooms of copepods and *V. cholerae* (Colwell, 1996; also see case study by Laws, this issue). Similarly, during the 1997–1998 El Niño event, winter temperatures in Lima, Peru increased more than 5°C above normal and the number of daily admissions for diarrhea increased by more than twofold compared to expected levels based on the prior five years (Checkley et al., 2000). Long-term studies of the ENSO have confirmed this pattern. ENSO has had an increasing role in explaining cholera outbreaks in recent years, perhaps because of concurrent global warming (Rodo et al., 2002).

Understanding inter-annual cycles of cholera and other infectious diseases, however, requires the combined analyses of both environmental exposures and intrinsic host immunity to a disease. When these factors are considered together, inter-annual variability of cholera is strongly correlated to SSTs in the Bay of Bengal, to ENSO, to the extent of flooding in Bangladesh across short time periods (< 7 years), and to monsoon rains and Brahmaputra River discharge for longer-period climate patterns (> 7 years) (Koelle et al., 2005).

CONCLUSIONS

There are several reasons to be concerned about the recent rise in atmospheric CO_2 and the resulting global warming. First, the change has been more abrupt than any we have seen in the geological record. Second, current practices and policies combined with the anticipated growth of the human population during the 21st century gives us little reason to believe that anthropogenic CO_2 emissions will decline. The IPCC (more information available at http://www.ipcc.ch) "business as usual" scenario indicates that by the year 2100 annual global CO_2 emissions will have increased to roughly 20 billion tonnes and the CO_2 concentration in the atmosphere to 700 ppmv (Houghton et al., 1996). Biological communities and human societies can presumably evolve and adapt in response to gradual change. It is unclear that they can adapt in a satisfactory manner to the impacts associated with a doubling or greater of the current atmospheric CO_2 concentrations during the 21st century.

As discussed above, this rapid and significant increase in atmospheric CO_2 concentrations and resulting climate change will lead to a number of adverse public-health outcomes through the interplay of societal and environmental factors. Increasing sea level and temperature can especially threaten the increasingly large populations that live in proximity to the oceans and/or derive their livelihoods from the sea. It is also important to recognize how parallel processes of environmental degradation can exacerbate these risks. For example, the destruction of coastal wetlands or mangrove swamps will lessen the protective capacity of these ecosystems against typhoons and storm surges. Excessive freshwater extraction, development, and building of levees that reduce sediment loading of deltas are leading to land subsidence. All three of these factors augmented the impact of the Hurricane Katrina disaster that struck the city of New Orleans in August 2005. This clear example demonstrates the close relationship among climate change, social factors, and ecological degradation. It is time to pursue a highly integrated and rapid global approach to reducing the health risks from climate change.

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