

## **WORLDWIDE POLLUTION OF THE OCEANS**

by

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The Twelfth International Conference on the Unity of the Sciences  
Chicago, Illinois November 24-27, 1983

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You must not lose faith in humanity.

Humanity is the ocean.

If a drop of it becomes dirty,

The ocean does not become dirty.

Mahatma Gandhi (1869-1948)

You must not lose faith in humanity.

Humanity is the ocean.

If a part of it becomes dirty,

Humanity will clean it up in unison.

Momiji

## INTRODUCTION

When we stand by the ocean it is difficult to fathom that we people collectively are capable of altering the ocean to the detriment of humankind. The ocean appears so vast and our anthrosphere so benignly minuscule. Conversely, we have witnessed methyl mercury poisoning of fish and shellfish from industrial wastes discharged into Minamata Bay, Japan, in the 1950s; over 100 people died and many more were damaged permanently.

The fact is from time immemorial we have been disposing of anthropogenic waste materials into the ocean. Agricultural pesticides enter the sea through rivers and stream. Lead emitted from automobiles into the atmosphere also precipitates over the ocean. Within the last century we have witnessed that some semiconfined bodies of water, such as Tokyo Bay, were being degraded seriously. Even in the open sea far from us some pollutants, such as plastic litter, are distributed worldwide.

As global industrialization intensifies and population increases, the pressure to dispose our wastes into the ocean, deliberately or inadvertently, will increase. This requires careful and critical evaluation of the ocean's capacity to accommodate the waste materials. Such evaluation is paramount to insure that valuable resources of the sea are preserved and protected for future generations. The basic science of oceanography must be nurtured as we use the ocean more for our waste disposal, without which it is not possible to attain a long-term solution.

### DEFINITION OF MARINE POLLUTION

The Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) comprised of eight United Nations organizations offers us the following definition:

Marine pollution means the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of seawater and reduction of amenities.

The substances mentioned here are (1) toxic metals such as mercury and cadmium, (2) synthetic organic compounds such as pesticides including DDT (dichloro-diphenyl-trichloroethane), (3) petroleum hydrocarbon compounds, (4) radioactive wastes, (5) solid wastes such as floatable plastic pellets, (6) sewage and industrial wastes, and (7) dredged material. The introduction of energy into the ocean may cause thermal pollution where, for instance, steam-electric power plants using large amounts of cooling water elevate the seawater temperature locally which may not be optimal for marine life inhabiting the area. Conversely, the introduction of energy may also cause thermal enhancement for culturing fish, shrimp and eels. Similarly, sewage nutrients, such as nitrogen fertilizers, may help oceanic primary

production. Therefore, it is important to view the substances and energy mentioned above as potential resources whenever possible.

### THE OCEAN AS A CESSPOOL

Our civilization past and present has used the ocean as a cesspool. What we have practiced is the method of dilution and dispersion for waste management. The GESAMP scientists make an analogy of the smoke-filled room to describe the oceanic dilution and dispersion concept.

Assume that there are several people in a room and one starts to smoke. A plume of smoke drifts and the people nearby are affected by the smoker's antisocial act. However, the turbulent currents of air gradually carry and mix the smoke to the farthest corners; the background level of smoke begins to build up. After a while the rate of increase of smoke concentration diminishes as the processes removing it begin to take effect; the removal processes include ventilation and deposition on curtain fabrics and in people's lungs. For the ocean the removal processes include water exchanges among various oceans and seas, sedimentation and incorporation in marine organisms.

Although the ocean is complicated due to stratification of water layers, the rotation of the earth, chemistry, biology, geophysics and geochemistry, the smoke-filled room analogy describes the major processes of dilution and dispersion and the processes of fluctuations and the steady-state in the near and far fields.

### THE OCEAN AS A WASTE REPOSITORY

Since the onset of the nuclear age in 1944, we also have used the deep-

sea floor to place low-level radioactive wastes. For instances, the United States placed one hundred and seven thousand canisters of nuclear wastes on the seafloor of the Atlantic and Pacific Oceans during 1946 to 1970. (The United States has not ocean-disposed of nuclear waste ever since.) The estimated total radioactivity at the time of disposal was  $4.3 \times 10^{15}$  disintegrations per second (about one hundred thousand curies).

The wastes were carefully packaged in metal drums with cement to isolate and contain the wastes from the deep-sea water and organisms. Many of these drums are still intact; in them radioactive decay continues.

This method of waste management is called isolation and containment and has been the preferred method to cope with highly toxic wastes and radioactive wastes. Since time and place of repository are known accurately, we can study the fate and effects of the wastes scientifically. In addition, when necessary, we can also retrieve the wastes to make them unarmful or redeposit them to safer places.

## THE DYNAMICS OF THE OCEAN

The ocean is dynamic. People-originated marine pollution is governed by the basic processes of the ocean. We must understand these processes to determine and forecast people's impact on the ocean.

Water moves. So does the seafloor. Scientists now know that the deep Atlantic Ocean water is about 200 years old while that of the Pacific Ocean is 500 years old. Seafloor spreading renews the bottom of the ocean; the oldest marine sediments in the Atlantic are 200 million years old, a relatively young age comparing with the age of the earth and ocean of several billion years.

Water evaporates from the ocean into the atmosphere. Man-made carbon dioxide in the atmosphere exchanges with the oceanic carbon dioxide; the seawater

carbon dioxide reservoir is about 50 times greater than that of the atmosphere. At the air-water boundary heat exchanges also. Practically all the rains we receive come from the ocean. The rains in turn change into runoff and return back to the ocean. In the runoff, eroded continental rocks, soil, and washed-out agricultural pesticides are carried into the sea.

The ocean may be considered a gigantic acid-base titration setup. Acids ejected from volcanoes, vents, and sulfur-rich coal burning are neutralized by alkaline substances from rocks. Today the pH (a measure of acidity and alkalinity) of the ocean is about 8, a slightly alkaline solution which is the product of a gigantic acid-base titration with better than 99% completion of the natural geochemical neutralization. Nature has proven to be a superb chemist who is better than many undergraduate students taking an analytical chemistry course.

We owe the present stable oceanic pH range to the silicate and carbonate minerals in the oceanic environment. The buffer capacity, which resists against pH change, of seawater is about two milliequivalents per liter (it takes about two milliliters of one normal hydrochloric acid to neutralize a liter of seawater). Lake waters' buffer capacity is much less than that of seawater. Thus, the acid-rain problem is severe in lakes but not so in the ocean. Recently Professor Iver W. Duedall of Florida Institute of Technology calculated the maximal contribution of  $12 \times 10^{18}$  kg (12 billion billion kilograms) of coal burning in neutralizing the alkaline oceanic waters; he obtained a value of 30% reduction of the oceanic buffer capacity. His concurrent calculation on the elevation of seawater temperature by the total coal burning was  $0.05^{\circ}\text{C}$ . It appears the ocean can survive against the onslaught of acid-rain in terms of pH and energy.

For many terrestrial and freshwater organisms the present chemical makeup of the ocean is not hospitable. Pristine seawater already possesses toxic substances dissolved in seawater and deposited in sediments. In our quest to understand the processes of marine pollution, we must accurately know the baseline concentration of the oceanic chemical elements and the processes leading to the establishment of the present makeup.

In general, seawater contains about 35 grams of salts in a kilogram of seawater (3.5% by weight). Dr. Peter G. Brewer of Woods Hole Oceanographic Institution tabulated its composition as shown in Table 1. Some of those numbers will be modified as we become more proficient in chemical analyses. Surprisingly the chemical composition is uniform among different oceans and regional seas. An analogy we can make here is the same as the smoke-filled room mentioned earlier; after many hours the smoke is widely distributed.

Seawater exerts over 20 atmospheres of osmotic pressure. Across biological membranes such as skin, osmoregulation is an important process to maintain life, without which the chemical makeup of body fluids cannot be maintained. Osmosis forces the water in body fluids to be transported toward seawater. (Ancient civilizations discovered the use of salt to dry and preserve herring). The organisms which adapted to osmoregulate can survive in the ocean.

Rivers add dissolved and turbid substances into the sea. Particle sedimentation and flocculation remove some of them; they accumulate on the seafloor. To illustrate the dynamics of the chemical substances, let us focus on copper as an example. Each year rivers add about 250 thousand tons of copper to the sea. Scientists discovered recently that the ionic form of copper is very toxic to marine life. Fortunately, near the river mouths vigorous photosynthesis occurs. The ionic copper thus becomes bound to organic substances; these complex



compounds do not possess the toxicity of ionic copper. Thus in reality, while our coastal fishing industry prospers, so reduces the toxicity of river-borne copper. Mother Nature mysteriously cleans the sea for marine life.

Dr. Brewer gives the copper concentration of seawater as 0.5 micrograms per liter (parts per billion). Where does the seawater-borne copper go when rivers, submarine volcanoes and vents continually eject copper into seawater? The majority of it will eventually settle onto the seafloor. Dean G. Ross Heath of Oregon State University and his colleagues show us that the copper content of the Pacific deep-sea ferromanganese nodules can exceed one gram per kilogram (part per thousand) (Figure 1). Mother Nature again continues to purify seawater for marine life. Incidentally, the copper-rich manganese nodules are commercially exploitable. When our future generation exploits them, we must study the re-entrance of sediment-bound copper and other toxic substances into the marine ecosystem.

I personally like to stress here that toxicity of an element is governed by its chemical forms, not solely by the elemental concentration. For copper it is the ionic copper we must deal with carefully. For cadmium, another toxic element, it also is its ionic form; when freshwater-borne cadmium mixes with seawater it forms chemical complexes with the chloride present in seawater resulting in reduction of its toxicity. So, cadmium is more toxic in freshwater than in seawater. For mercury, it is methyl mercury (an organic compound) that killed over 100 people and maimed over 700 others in Japan. Scientists are studying the chemical speciation and complex formation of toxic elements in the ocean. Some important breakthroughs are being made. For instance, we now know the mechanism of a detoxifying protein, metallothionein, that sequesters toxic metals, such as mercury and cadmium, in marine organisms.

The purpose of our collective effort to minimize marine pollution is to assure the safety of people. The marine ecosystem, and to insure the integrity of the marine environment for the continuation of life. Life in the sea is not correctly depicted by the placid display of aquariums all over the world. Struggles for existence and for continuation of species take many different forms. The late John Dove Isaacs (1913-1980) spoke, "It is not in the terrestrial experience continuously to inhale the young, eggs, sperm, food and excreta of all our fellow creatures.... Although it may seem repulsive to us, it, nevertheless, is the way of marine life."

As the human population burgeoned ahead, we have added two major complexities to marine life. We overfish and pollute. We may also enhance marine life by adding human excreta into the sea. The dynamics of marine biota is affected by all of these activities. Sharon A. MacLean of Oxford Laboratory in Maryland, U.S.A., offers me the following relationship to ponder upon:

$$V = F + P + E + M$$

Where V: population variability

F: fishing pressure

P: predation

E: environment stress factors (e.g. temperature, chemical pollutants)

M: natural mortality

We people have collectively proven that we can overfish; the past exhaustive whaling is a notable example. Environmental factors are both natural and man-induced. The El Nino phenomenon along the Peruvian coast destroys anchovy fishing and consequently guano production by predator-birds. Finrot disease occurring

among winter flounder off New York City is related to the magnitude and distribution of chemical pollutants in the marine sediments; it likely raises the fish's susceptibility to predation. It appears that people control the population variability of fishes in many ways, directly and indirectly.

I would like to depart from the ocean for a moment. Professor Robert M. Garrels of University of South Florida once asked me, "Is the ocean a producing or consuming environment?" His profound question urges us to determine the inflow of organic substances from the land biosphere into the ocean as compared with their removal by sedimentary deposition and overfishing. The present marine biomass is estimated at 100 billion tons. The land biosphere produces over ten times that each year. An annual yield of fishing during 1975-1978 was about 70 million tons. If we assume that there has been a delicate balance between the land and oceanic organic reservoirs, how will alteration of the land biosphere by people affect the oceanic biosphere? If the ocean were a consuming environment heretofore, what would be the effect of less inflow of organic material due to land pollution and alteration? If the above relationship is significant, then land pollution will affect the welfare of the ocean in a fundamental way.

Dr. Leo S. Gomez of Sandia National Laboratories and his colleagues give us a drawing showing representative marine biota (Figure 2). Of the marine biomass of 100 billion tons, 67 billion tons are bottom-dwelling organisms, of which 55 billion tons are distributed in the shoal waters of the continental shelves. Below 3000 meters, 0.56 billion tons of bottom-dwelling organisms cover the vast seafloor. Therefore, these great depths of the oceans are comparable to that of terrestrial deserts.

## MAN'S IMPINGEMENT

President John A. Young of Hewlett-Packard Company wrote an important editorial entitled "Quality: The Competitive Strategy" in *SCIENCE*, issued on 4 November 1983. He spoke "... pursuing quality is a cost-competitive strategy and that efforts to achieve quality must begin in the design phase of a product. Some of our greatest improvements have been the results of designers working closely on processes with people in manufacturing, on parts specifications with our vendors, and on applications needs with our customers." His statement is directly applicable to our quest to cope with worldwide marine pollution. Waste management experts including oceanographers must work in the design phase of industrialization rather than be left at the back-end of it. Chess games are often decided by the end-games in which winners strategically have placed their pawns well; these pawns may be the waste management specialists. In the case of the Minamata Bay mercury poisoning, the Chisso company by 1975 had paid indemnities totaling more than \$80 million to the people affected; their inadequate waste management had cost dearly.

The majority of the present marine pollution problems is due to our shortsightedness and inexperience. In addition, the ocean, an international resource, does not have a comparable constituency to what we witness in coastal protection, urban air pollution, drinking water fluoridation, and noise abatement. The ocean is not protected as vigorously and urgently as is the land. Mankind has been fortunate to rely on the yet-to-be-quantified oceanic ability to cleanse and renew itself.

There are several modes for pollutants to enter the ocean. They are (1) river discharge, (2) atmospheric transport followed by precipitation into the sea, (3) coastal discharge through outfalls, (4) sea-going vessel generated pollution, and (5) ocean dumping. Contrary to our earlier perception, DDT and its degradation products and PCBs (polychlorinated biphenyls) primarily enter the ocean from the

continents via the atmosphere, in addition to river runoff.

Professor Edward D. Goldberg of University of California at San Diego estimates that three billion tons of wastes are produced annually by us; that is about ten times the total human body weight on earth, requiring much care and energy to manage these wastes. In addition, we are in the midst of an epoch in human history of fossil-fuel exploitation (Figure 3). Fossil-fuel burning of over two million billion kilowatt-hours (65 percent of from burning two million million tons of coal) during the next several hundred years will add further oxides of carbon, sulfur, and nitrogen into the atmosphere as pollutants. A substantial amount of these wastes eventually reaches the ocean. I also should mention the impact of the change in land use by people. Deforestation and construction of roads and cities would augment the entrance of man-induced pollutants into the sea via the atmosphere and runoff.

The components of the earth system are all connected and interwoven. The amount of materials people move over the surface of the earth, three billion tons per year, is almost ten percent of nature's activity through her weathering cycle; it is the same magnitude of substances that glaciers currently transport into the ocean.

## **METALS**

The tragic deaths of over one hundred people by methyl mercury poisoning in Minamata have taught us many lessons. We have learned that we must pay attention to the toxicity of metals and their various ionic and complex substances, the persistence of these in the marine environment, and marine food web magnification (bioaccumulation).

Virtually all metals are found in the ocean (Table 1). Some metals such as mercury, silver and copper are extremely toxic while others are innocuous to marine organisms. Dr. Michael Waldichuck of Canada Department of Fisheries and Oceans gives us the following order of toxicity of cationic metals to marine life:

mercury > silver > copper > zinc > nickel > lead  
cadmium > arsenic > chromium > tin > iron > manganese  
aluminum > beryllium > lithium

For mercury we learned that methyl mercury, an organic complex, is highly toxic and readily soluble in body fats.

Five tragedies of human poisoning due to toxic metals have been documented in Japan. They are mercury poisonings in Minamata Bay (1953-1960), in Niigata (1964-1965), and in Goshonoura (1973); cadmium poisoning in Fuchu (1947-1965); and chromium poisoning in Tokyo (1975). In each case these metals in sediments were transferred through the marine food web and subsequently were consumed by people. Therefore, it is important to learn the mechanisms of metal transfer from sediments to marine life.

Any significant increase in toxic metals in seawater, sediments, and marine life presents us an early warning signal. A group of international scientists has initiated a global mussel watch. Along the east and west coasts of the United States numerous sampling stations were set up in 1976. Dr. John W. Farrington of Woods Hole Oceanographic Institution reports that the sentinel program is working well. For instance, cadmium was taken up by the mussels along the central California coast during the period of coastal upwelling of deep-sea water during the summer months; its magnitude was about four micrograms per gram of dry mussel tissue (part per million) while at other mussel sampling stations its magnitude was

about one-half that.

Both mercury, cadmium and their compounds are prohibited to be ocean-dumped by an international agreement (London Dumping Convention), while metallic substances requiring special care are arsenic, lead, copper, zinc, and their compounds. As an example of global concern, mercury pollution is discussed below.

Mercury is dangerous for man. Sensitive human adults show symptoms of mercury poisoning at a weekly intake level of 1.3-2.9 milligrams. The Minamata victims consumed about 14 milligrams of mercury per week. Mercury levels tolerated by the United Nations World Health Organization (WHO) and the United Nations Food and Agriculture Organization (FAO) in human food is a weekly consumption of up to 0.2 milligrams of methyl mercury or 0.3 milligrams of total mercury; this incorporates a safety factor of tenfold. Professor Dr. Sebastian A. Gerlach of Institut für Meereskunde, Kiel, informs us that an average citizen in the Federal Republic of Germany has a weekly intake of 0.2 milligrams of mercury (20% from grain, 15% from beer and other alcoholic beverages; 10% from milk and butter, 8% from fish and the remaining come from other sources). The mercury concentration of fish is in general in the order of 0.1 milligram per kilogram, mostly as methyl mercury. Therefore, weekly consumption of two kilograms of fish alone would be the upper limit of tolerable mercury intake.

Let us examine the mercury content of the ocean. Total mercury in seawater is about seven million tons. Each year rainfall over the ocean adds about four thousand tons and rivers add one thousand tons. The world population of mercury in 1968 was about nine thousand tons. If one-half of the man-made mercury entered the ocean, its magnitude would be comparable to the natural addition of rainfall and rivers combined. Sedimentation onto the seafloor may remove one thousand tons of mercury per year. Thus, this rough calculation shows that the net addition per annum of mercury by nature and man is in the order of

0.1% of the total seawater mercury content. As such, open ocean fishes far away from the coast will not show an increase in mercury concentration as a result of man's input. However, pockets of local pollution near industrial activities may show mercury contamination in sediments and biota. For instance, in the Santa Barbara Basin off California the mean mercury concentration in sediments increased twofold in recent years when compared with that of the preindustrialization era (Figure 4).

An important concern we have about mercury is that mercury concentrates as it goes upward through the marine food web. Recent studies by Willard Bascom and his coworkers at Southern California Coastal Water Research Project, Long Beach, yielded fundamental data on bioaccumulation. Henry A. Schaefer and colleagues at the Project showed that mercury concentration increases with the advancement of trophic level. Top predators, such as silk shark, mako shark and spiny dogfish, had a similar mercury concentration of 1.5 milligrams in a kilogram of wet edible muscle (Figure 5). However, one white shark contained an unusually high value of 8 milligrams per kilogram, possibly due to age.

Since we, too, are the top predators it is possible to bioconcentrate mercury in our bodies. To reduce it, it is prudent to eat fishes with low mercury content. Candidate fishes may be large zooplankton such as krill, anchovies, sardines and squid; their mercury concentrations reported by Schaefer and his coworkers are in the range of 0.02 to 0.05 milligrams per kilogram. Conversely, bonita, barracuda, yellowfin tuna, and frigate tuna contain mercury in the range of 0.2 to 0.3 milligram per kilogram.

## SYNTHETIC ORGANIC SUBSTANCES

Our technological society has been synthesizing many new organic substances for our civilization. Wastes generated by the production and use of



these substances are adding foreign matters which did not exist before to the sea. Scientists have coined a new name for these alien substances which affect the marine ecosystem; they are called xenobiotics.

A particular concern we have is that some harmful xenobiotics may accumulate in the ocean since nature may not be capable of degrading them to innocuous substances. Conversely, since the ocean did not have these xenobiotics before man introduced them, they become man-made tracers to understand the dynamics of the ocean (Figure 6). For instance, chlorinated hydrocarbons such as DDT and PCBs were found in the biota (plankton, sponges and fish) of Antarctica though at low levels, in the order of one part per billion (wet weight) or less. The eggs of Antarctic penguins contained them also.

Among various xenobiotics, chlorinated hydrocarbon compounds, such as DDT, PCBs, hexachlorobenzene (HCB) and Mirex, have been studied in the marine environment because they caused ecological damage. For years to come, even if the manufacturing of these chemicals is halted, I believe there should be continuous research on them for two reasons. The first reason is that the xenobiotics already produced will enter the ocean in any case. The second reason is to learn the processes associated with the recovery phase of the ocean from the insults.

It took 20 years to learn how DDT and its residues caused egg-shell thinning and consequent reproductive failure in sea birds. The brown pelican population of Anacapa Island off California had drastic decreases from 1969 to 1972. Professor R. Risebrough of University of California attributed it to egg-shell thinning due to DDT residues, mainly DDE (dichloro-diphenyl-ethylene). With DDE concentrations of about five and 70 parts per million in the pelican eggs, the egg shells became thinner by 15 and 35 percent, respectively (Figure 7). As a consequence of the thinning, the eggs broke quite easily. The source of the DDT residue was a factory in Los Angeles that discharged about 200-500 kilograms of

the residues everyday to the sea through the Los Angeles sewage system. These DDT residues were bioaccumulated by fish (Figure 5) and the fish were eaten by the pelicans.

The DDT story gives us lessons. The first is that damage to the marine ecosystem can be manifested in the avian domain. The second is that sea birds can be our sentinels to monitor the extent of marine pollution.

The World Health Organization established an acceptable daily intake limit of 0.3 milligrams of DDT per person. The edible muscle of cod caught at George's Bank in the Atlantic Ocean in 1971 contained about 0.01 milligrams per kilogram (wet weight) of DDT and its residues. Therefore, DDT does not pose any significant harm to people who enjoy George's Bank cod. In fact, no harmful effect of DDT upon human health has been observed. In experiments, however, concentrations of one part per billion of DDT in seawater showed a toxic effect on diatoms (phytoplankton) from the Sargasso Sea.

The worldwide production of DDT increased from the 1940s to the 1960s. An estimate given is that almost three million tons were produced and used up by the year 1974. Recently, the use of DDT became prohibited in some countries; the United States banned its use in 1972. In recent years, concentrations of DDT and other pesticides in marine organisms and sea birds have been decreasing (Figure 8). Interestingly, the population of brown pelicans in California is increasing. The DDT story demonstrates that we people collectively can reverse marine pollution. The knowledge we persistently have gained in research, monitoring, and vigilance with an open mind has helped to eliminate a cause of pollution. A program of action without a program of learning often is ineffective and costly. I personally salute the dedicated people of learning and of action for their 20-year effort to understand the dynamics of DDT in the marine environment.

Polychlorinated biphenyls (PCBs), like DDT, are associated with the lipid

part of marine life; they inhibit the growth of diatoms at as low a level as 25 parts per billion, and kill juvenile shrimp at five parts per billion in seawater (75% mortality in 20 days). In 1968 over five thousand people in Japan experienced PCB poisoning with chloracne-like skin eruption; four deaths were attributed to PCBs. The WHO reports that skin effects may occur in man at a daily ingestion of 4.2 milligrams of PCBs; there have been no acceptable standards established by the WHO for daily intake of PCBs by humans.

The PCBs are highly stable, non-flammable, and have low water solubility, low volatility and they do not conduct electricity but can sustain an electric field. Therefore, they were used in electric transformers and capacitors. They were also used as hydraulic fluids in high temperature systems. Other uses included PCBs as plasticizers, lubricating and cutting oils, sealants, and as components in paints and printing inks. Therefore, PCBs were broadly distributed and from those sources the ocean has received them (Figure 6).

About one million tons of PCBs have been produced worldwide; the United States has produced about 50% of them. In 1971, PCB production (in tons) for several industrialized countries were as follows: United States 18,000; the Federal Republic of Germany 8000; France 7600; Japan 6800; the United Kingdom 5000; Italy 1500; Spain 1500. The PCBs, too, appear to be transported primarily from the continents through the atmosphere to the ocean. Recognizing the threat of PCBs to environmental resources, many countries began reduction or cessation of PCB manufacturing. In 1977 the United States ceased their production. At present, spent PCBs are collected and incinerated at sea.

In most cases PCB concentrations in fish are less than those in meat of 0.3 milligrams per kilogram. For instance, the edible muscle of cod from George's Bank in 1971 had a PCB concentration of 0.04 milligrams per kilogram. In some locations, though, PCBs are concentrated in the sediments and may make their way

into the food web. For instance, in 1978 the U.S. mussel watch program detected heavy PCB pollution in New Bedford Harbor, Massachusetts. The PCB concentration in mussels was as high as 31 milligrams per kilogram; this was six times greater than the U.S. Food and Drug Administration's recommended upper limit of 5 milligrams per kilogram in seafood for human consumption. This discovery occurred a year after the cessation of PCB production in the United States. The PCBs had entered the harbor area via two electrical component manufacturing companies nearby. How we will remove the New Bedford Harbor PCBs safely is a challenging operation; we should learn from it.

From the PCB and other studies we became keenly careful to recognize substances which are not suitable for our environment. The criteria we want to know are the substance's (1) toxicity, (2) persistence, and (3) accumulation in the environment (ecosystem). In some countries PCTs (polychlorinated terphenyls) were produced as a flame-retardant and for the production of paints and glues. Japan alone produced 2700 tons of PCTs from 1954 to 1972. When PCTs were known to be toxic, persistent and accumulating, Japan and the United States ceased its production in 1972. I advocate the toxicity-persistence-accumulation criteria test be applied by manufacturers before a new chemical emerges in our society.

### **PETROLEUM HYDROCARBON COMPOUNDS**

On 16 March 1978 the super tanker *Amoco Cadiz* was grounded off the coast of northern Brittany, France, and its entire 200,000-ton cargo of Arabian crude oil and bunker fuel was released into the marine environment. Sea birds, mussels and other marine life were affected catastrophically. Other similar events are reported occasionally including offshore oil well blow-outs. For instance, the Ixtoc-I platform spill of 1979 in the Bay of Campeche released 400,000 tons of

crude oil into the Gulf of Mexico. Major sources of petroleum hydrocarbon compounds enter the ocean unobtrusively in small quantities scattered over many shipping lanes (Figure 9) and along coastal zones. In 1975 the U.S. National Academy of Sciences compiled the major input sources per year as follows:

Transportation activities	2,100,000	tons
River runoff	1,600,000	
Atmospheric fallout	600,000	
Natural seeps	600,000	
Urban runoff	300,000	
Industrial wastes	300,000	
Municipal wastes	300,000	
Coastal refineries	200,000	
Offshore oil production	___100,000	
TOTAL	6,100,000	tons

The above estimate includes 200,000 tons per year for tanker accidents within the transportation activities input of 2.1 million tons.

Transportation-related input of petroleum is one-third of the total. It results from operational discharges. For instance, after discharging cargo oil, tankers on a return voyage fill the cargo tanks with seawater to maintain stability. The resulting mixture of ballast seawater and residual cargo oil is pumped overboard before arriving into port. Efforts are being made to reduce the oil content in ballast and tank-cleaning water.

Crude oils are complex mixtures of thousands of hydrocarbons (organic compounds composed solely of carbon and hydrogen atoms), trace amounts of metals such as nickel, vanadium and iron, plus porphyrins, and various organic compounds containing sulfur, nitrogen and oxygen. The deleterious effects of petroleum to living organisms include mechanical clogging and blanketing, irritation to mucous membranes and respiratory surfaces, and the chemical toxicity of aromatic hydrocarbons which contain one or more highly toxic benzene rings and other harmful substances. Many scientists, therefore, have been focusing on the fate and effects of aromatic hydrocarbons and their metabolic and degradation products. For instance, Dr. Donald C. Malins of Northwest and Alaska Fisheries Center, Seattle, inquires into the putative relationship between the formation of metabolic products coming from aromatic hydrocarbons and the onset of tumor growth and other cellular aberrations in marine organisms. We also know now that aromatic hydrocarbons are soluble in lipids and can accumulate in fish. In the marine environment they settle to the seafloor by attaching to sinking particles.

People, too, can be affected. Shortly after the 1978 **Amoco Cadiz** oil spill, nearby residents experienced headaches, dizziness, nausea, sensation of inebriation, vomiting, and abdominal pains. Skin irritation occurred among people who had direct contact with the oil. Carcinogenic aromatic hydrocarbons may be accumulated by food organisms and consumed by humans.

Petroleum discharged into the ocean may go through various processes that include evaporation, dissolution into seawater, emulsification, agglomeration, dispersion, sedimentation, photochemical oxidation, and microbial biodegradation. Mousse and tar balls, too, are produced. Eventually, biodegradation, however slow, will self-purify the marine environment.

An overriding problem facing the scientists who study petroleum pollution is its immense analytical difficulty. Even sophisticated analytical techniques can only

measure a small part of the complex sample. Aromatic hydrocarbons with one to five benzene rings can be determined, but not the polar components of crude and refined oils. Also, since petroleum hydrocarbons are often associated with DDT, PCBs, and other toxic substances, their combined effects of synergism and antagonism must be studied to know what actually happens in nature.

## RADIOACTIVE POLLUTION

By far the largest radioactivity input to the ocean by man is atmospheric fallout generated by over 1200 nuclear tests. In 1961 and 1962 about 50 billion billion becquerels (disintegrations per second) of radioactive hydrogen, hydrogen-3, entered the atmosphere as heavy water via atmospheric hydrogen bomb testings. It then exceeded the natural radioactive hydrogen inventory by about one hundred times. Since hydrogen-3 loses one-half of its radioactivity after 12 years, we have one-fourth of the original radioactivity at present. Professor Gote Ostlund of University of Miami and his colleagues measure the hydrogen-3 distribution in the ocean (Figure 10). In 1972 they discovered that hydrogen-3 penetrated down to almost five kilometers in depth in the high latitudes of the North Atlantic Ocean. They also found it spread over 3000 kilometers horizontally at depths between one and two kilometers.

Other military wastes exist in the ocean. They resulted from the accidental sinking of two nuclear submarines and the loss of airborne nuclear weapons near Palomares, Spain, and Thule, Greenland. In addition, satellites with nuclear power generators have fallen to the earth. They all may constitute an appreciable, yet not quantifiable, source of man-made radioactivity in the ocean.

On the other hand, radioactive waste disposal by our society has been minimal in comparison with the fallout. The United States disposed 107,000

canisters of low-level wastes from 1946 to 1970 with a total radioactivity at the time of disposal of 4.3 million billion becquerels. The only active dumpsite in the ocean today is in the northeastern Atlantic Ocean (Figure 11); during the 12-year period of 1967 to 1979 this site received 22 million billion becquerels of radioactivity. Nuclear fuel reprocessing plants discharge a similar magnitude of radioactivity into coastal waters as effluent.

Contrary to our perception, the ocean is naturally radioactive. One liter of seawater gives off eleven becquerels from potassium-40 radioactivity. Therefore, the entire ocean possesses 15,000 billion billion becquerels of radioactivity in seawater. In addition, deep-sea sediments are reported to have 500 to 20,000 becquerels of radioactivity in one kilogram while manganese nodules scattered over the seafloor have 6000 to 200,000 becquerels in one kilogram. Human bodies, too, are radioactive; a living human adult contains carbon-14 and potassium-40, each of which emits 4000 disintegrations per second. Therefore, when we study radioactive pollution, we should consider the level of natural radioactivity as a baseline.

What are the effects of radiation? Acute and massive exposure experienced by atomic bomb victims resulted in vomiting, convulsions, tremor, loss of muscular control, and subsequent death. Lesser effects included diarrhea, fever, damage to bone marrow, infection, loss of hair, hemorrhage, fatigue, and loss of appetite. Small amounts of radiation may initiate cancer and genetic defects in offspring. For instance, leukemia among the 1945 atomic bomb survivors was discovered three years after the blast and peaked in 1953. On the other hand, minor damages due to radiation can be repaired within our bodies.

The ocean has not received any high-level radioactive wastes. These wastes are being stored on land. According to U.S. NEWS & WORLD REPORT, 15 August 1983 issue, we have accumulated 8000 tons of high-level wastes in temporary underwater storage on land.



We have been in the nuclear age for 40 years. Regardless of an individual's view on the future of nuclear technology for power and weaponry, nuclear wastes are already with us. We have a responsibility to future generations to find a safe disposal method and safe disposal sites as well as to develop an adequate contingency plan which will be utilized if our chosen plan becomes unusable. What is safe? Could the ocean be a safer place than land since we live on land? Are we rational enough to transcend over our NIMBY (not in my backyard) syndrome for the sake of humanity? Our choice needs careful consideration and consensus.

### SOLID WASTES

Over six million tons of solid wastes are inadvertently scattered over the sea every year. Most of this garbage affects coastal areas. Some of it sinks and some floats. It consists of paper, metal, textiles, glass, plastic, rubber and wood. While this kind of waste does not pose a direct hazard to us most of the time, ship's propellers may become entangled by nylon ropes and plastic sheets. For this and other reasons, throwing garbage overboard from ships is discouraged. In fact, there is an international agreement by the London Dumping Convention to prohibit the disposal into the sea of "persistent plastics and other persistent synthetic materials, for example, netting and ropes, which may float or may remain in suspension in the sea in such a manner as to interfere materially with fishing, navigation or other legitimate uses of the sea."

Recently Professor Dana R. Kester of University of Rhode Island visited a preserved wildlife island off the coast of New Zealand. While impressed with the birds walking between his legs without fear, Professor Kester noticed the blight of marine litter, plastic artifacts of man, scattered along the shore. Amenities uplift

the human spirit; litter strewn beaches do not.

In addition to visual litter along a shoreline, persistent plastic is distributed widely in the ocean. In the Sargasso Sea, 3500 plastic pellets were netted on the average within an area of a square kilometer. Some plastic particles are ingested by organisms; they have been found in the intestines of many marine animals. We collectively must minimize the release of these persistent wastes to the environment. Professor Kester advocates that we strive to make synthetic products that are environmentally degradable by microorganisms, chemical decomposition, or ultraviolet photolysis.

### **SEWAGE AND INDUSTRIAL WASTES**

On 30 December 1675, Governor Edmund Andros, second English Governor of the Colony of New York, forbade any person to "cast any dung, dirt, refuse of ye city or anything to fill up ye harbor or among ye neighbors under penalty of forty shillings". Today more than 18 million people live around New York's coastal ocean; this region houses a giant industrial complex and shelters the world's busiest port. The peopling of this area made a maganimous jump from less than 20 thousand in the middle of the 17th century to today's population. Along with it, the coastal water have received and been stressed by the inhabitants' wastes, both domestic and industrial. Municipal sewage, storm watar runoff and industrial discharges find their way to the coastal ocean. And the New York story is being re-enacted at other megalopolis. Dr. Donald F. Squires of the New York Sea Grant Institute, Albany, solicits that we learn about the interactions of man and the ocean from the extensive information already available in this region.

Sewage contains organic matter, nutrients such as phosphate, bacteria, viruses, and parasitic worms. Some of these bacteria and viruses are pathogenic.

When industrial effluents are connected to sewage systems, as is done in New York, a wide range of chemical substances, including oil and metals, enter the sewage systems and subsequently into the sea. Sewage may reach the sea untreated via storm sewers or treated before discharge. The treatment can be mechanical settling of particles (solids), or additional biological or chemical treatment to break down organic matter. Treatment produces effluent and sludge; they are disposed of separately. The sludge from New York is ocean-dumped at a site 20 kilometers from the coast.

The worldwide quantity of sewage wastes disposed into the ocean is proportional to the population size of the coastal inhabitants. When possible, people use sewage for agricultural and aquacultural enhancement. The total sewage sludge the United States produced in 1979 was about 6 million dry tons. Since an average solid content may be about 3%, the wet sludge coming from sewage treatment plants is about 200 million wet tons. Of it approximately 6 million wet tons of sludge were ocean-dumped off New York and about 3 million wet tons were discharged into the seas through outfalls at Boston and Los Angeles. Therefore, about 5% of the sewage sludge of the United States goes into the ocean. For the United Kingdom, a higher percentage of sewage sludge may enter the sea since oceanic sludge disposal is practiced widely there. In 1979 about 17 million wet tons of sewage sludge were ocean-dumped by the London Dumping Convention member states (Figure 12).

Transmission of infectious diseases is a major concern of sewage waste disposal for both effluent and sludge. Gastrointestinal illness can occur as a result of bathing in and consuming shellfish from contaminated sites. During the past decade several outbreaks of infectious hepatitis, shigellosis and cholera have been attributed to either swimming in or eating shellfish taken from sewage contaminated areas in the United States. Chlorination of the sewage effluent has been attempted

to eliminate the disease organisms, but carcinogenic chlorine-containing compounds may be produced in seawater inadvertently.

The oceanic disposal of industrial wastes is well documented by the International Maritime Organization (IMO) which is the secretariat to the London Dumping Convention. For the year 1979 approximately 18 million tons of the wastes were disposed in the ocean (Figure 12). Some industrial wastes also enter the sea as effluent. However, stringent regulations are enforced to prevent any toxic effluent from entering the environment.

The industrial wastes ocean-disposed include mixtures of hydrochloric or sulfuric acids with iron that are generated in the production of titanium dioxide pigment, diluted acids, fish offal, ammunition, copper-containing dilute acid, coal ash and colliery wastes, drums and cannisters, construction debris, various pharmaceutical wastes, and sodium sulfate solutions. In the Gulf of Mexico metallic sodium was ocean-dumped in the 1950s and 1970s.

I raise concern over the wisdom of connecting domestic sewer systems with industrial effluent systems. Such mixed wastes may be treated ineffectively at sewage treatment plants. In addition, much of our domestic waste can be utilized as fertilizer, especially for silviculture and land reclamation in abandoned open-pit mines. Utilizable wastes should be reused rather than mixed with other, perhaps toxic, wastes. In June 1983 I visited a small sewage treatment plant amidst an apartment complex of 20 thousand inhabitants in Shanghai. The plant separates sewage into effluent and sludge. The effluent is discharge directly into a river nearby and the sludge is carted off to farmland around Shanghai. Thus, the sewage of 20 thousand people is treated at the source and the usable part recycled before it gets mixed with the industrial waste of Shanghai.

## DREDGED MATERIAL

Dredging of waterways and harbors is a continual process in order to maintain marine transportation. Dredge spoil problems occur when coastal and harbor sediments are contaminated by pollutants from municipal, shipping and industrial sources. Conversely, non-polluted dredged material is a resource to nourish beaches, to reclaim land, and for construction (sand).

The global magnitude of dredge operations is difficult to estimate. The International Association of Ports and Harbors (IAPH) asked 70 countries to report their dredging activities to IAPH; it obtained 108 responses from 37 countries. Based on them Professor Kester estimated that 350 million tons of maintenance dredging and 230 million tons of new construction dredging had occurred in 1979. It appears, therefore, global dredging activities are in the order of one billion tons per year. Contaminated dredged material may be a small fraction of the total.

The substances of concern are toxic metals, synthetic organic substances such as DDT and PCBs, and oil and grease; their concentrations vary depending on the proximity to and magnitude of the original contaminant sources. Pathogens in the sediments are also of human health concern. One of the most important considerations is the remobilization of toxic substances and pathogens from the sediment phase to the water phase above and to the biota. Scientists now know that zinc is released from sediments at low pH (around 5) when seawater still contains some dissolved oxygen; they also know now that copper is released easily when the dissolved oxygen content is very high.

What should we do with highly polluted dredged materials? In order to isolate them, capping experiments have been conducted in the United States and Canada. Contaminated sediments are capped with clean sediments to immobilize toxic substances. There is an artificial island, Craney Island, near Norfolk, Virginia, constructed to isolate the spoils. Here we try to immobilize and isolate them

simultaneously.

## DISCUSSION

When the dissolved oxygen content of seawater decreased off New York and shellfish died en masse in 1976, marine pollution was blamed as its cause (Figure 13). Scientific studies showed later that an extensive bloom of a phytoplankton (dinoflagellate, Ceratium tripos) was its cause. Though the unusual weather and oceanic conditions helped the phytoplankton to bloom and decay, thus causing depletion of oxygen from the bottom water, an important question still remains: To what degree had human polluting activities contributed to the anoxic event? Are we the catalyzing agent? If so, man's action can be amplified with resultant mass killing of marine organisms.

In the Baltic Sea where bottom water is not replenished readily with oxygen from the atmosphere or the North Sea, the bottom-dwelling organisms live on precariously. In recent years conditions have worsened. For instance, in 1900 in the nearbottom water of Landsport Deep oxygen was measured at 2.5 milliliters per liter of seawater; by 1950 it decreased to 1.5 milliliters; recently on occasions no oxygen was detected and bottom organisms were dead (Figure 14). Baltic marine scientists are asking the same question the scientists of New York area ask: What fraction of the anoxic event is due to people-originated pollution? The Baltic scientists know now that eutrophication is occurring in the surface waters; dead organic substances then rain over the bottom and deplete the water of oxygen.

The oxygen stories of New York and the Baltic are not isolated events. They will happen again and at other places. Fundamental oceanographic knowledge of the regions which are likely to be polluted must be known. It takes time to know the oceanic processes in each region. Competent students must be trained.

Realizing the importance of obtaining long-term solutions to marine pollution problems which includes education and training, Professors Kester and Duedall of the United States in 1977 began laying the groundwork to convene international ocean disposal symposia. This symposium series meets once every 18 months to discuss among scientists the new findings associated with marine waste disposal practices. The participants live in a dormitory; students from many countries are supported to attend; discussions continue late into the evenings; new contributions are published as books. The fifth symposium will be held at Oregon State University, Corvallis, 10-14 September 1984, under the chairmanship of Dr. Judith M. Capuzzo of Woods Hole Oceanographic Institution. As at Plato's academy, mathematics and other scientific languages are spoken at these forums. In addition to forging the scientific frontier ahead, the several quality seeds (students) nurtured through this cradle may be a cost-competitive strategy to cope with future marine pollution problems. Rome was not built in one day.

People in and around heavily stressed coastal regions and semi-confined water bodies must solve their pollution problems by themselves. The knowledge thus gained will help us protect the integrity of the presently healthy vast ocean. Each of us, by our cumulative actions, may help keep the ocean alive for generations to come.

In the future we will use the ocean more for our welfare. Ocean thermal energy conversion (OTEC) may produce the energy needed by us in the future. Ocean mining of manganese nodules will give us valuable metals such as copper, cobalt, nickel, manganese and others. All the planners of these new undertakings must consider the total activities from the front end to the back end (waste management). The only nest we have is the Earth.

## ACKNOWLEDGMENTS

I thank Sharon A. MacLean for valuable discussion and reviewing and LaTina Conrnish for typing. I dedicate this writing to the people of learning and action who unselfishly have been working to know about and to prevent global marine pollution. Especially I honor my predecessors who in their lives assisted me to recognize that knowing harmony is permanence and, therewith, enlightenment; they are the late Drs. Max Blumer and Bostwick H. Ketchum of Woods Hole Oceanographic Institution, the late Professor Dr. Klaus Grasshoff of Institut fur Meereskunde, Kiel, and the late Professor John D. Isaacs of Scripps Institution of Oceanography.

## RECOMMENDED READING MATERIAL

In recent years many new reports and books on marine pollution have been issued. They are informative, educational and futuristic. Though the present ocean away from degraded coastal and estuarine regions is remarkably healthy, my view is that we have a chance to preserve and use the ocean in a sensible manner in time rather than manage the ocean by crisis response. We are the people of learning and action. To write this article I heavily have used the following publications. I recommend them to you for your learning.



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Table 1. The concentration of chemical elements in seawater.

The units given are mg/l (milligram per liter),  $\mu\text{g/l}$  (microgram per liter), and ng/l (nanogram per liter). One gram (g) is 1000 mg, or 1,000,000  $\mu\text{g}$ , or 1,000,000,000 ng.

	mg/l		$\mu\text{g/l}$		ng/l		ng/l
Chlorine	18,800	Zinc	4.9	Xenon	50	Lead	2
Sodium	10,770	Argon	4.3	Cobalt	50	Tantalum	2
Magnesium	1,290	Arsenic	3.7	Germanium	50	Yttrium	1.3
Sulfur	905	Uranium	3.2	Silver	40	Cerium	1.0
Calcium	412	Vanadium	2.5	Gallium	30	Dysprosium	0.9
Potassium	399	Aluminum	2.0	Zirconium	30	Erbium	0.8
Bromine	67	Iron	2.0	Bismuth	20	Ytterbium	0.8
Carbon	28	Nickel	1.7	Niobium	10	Gadolinium	0.7
Strontium	7.9	Titanium	1.0	Thallium	10	Praseodymium	0.6
Boron	4.5	Copper	0.5	Tin	10	Scandium	0.6
Silicium	2	Caesium	0.4	Thorium	10	Holmium	0.2
Fluorine	1.3	Chromium	0.3	Helium	7	Thulium	0.2
Lithium	0.18	Antimony	0.2	Hafnium	7	Lutetium	0.2
Nitrogen	0.15	Manganese	0.2	Beryllium	6	Indium	0.1
Rubidium	0.12	Selenium	0.2	Mercury	5	Terbium	0.1
Phosphorus	0.06	Krypton	0.2	Rhenium	4	Samarium	0.05
Iodine	0.06	Cadmium	0.1	Gold	4	Europium	0.01
Barium	0.02	Tungsten	0.1	Lanthanum	3		
Molybdenum	0.01	Neon	0.1	Neodymium	3		

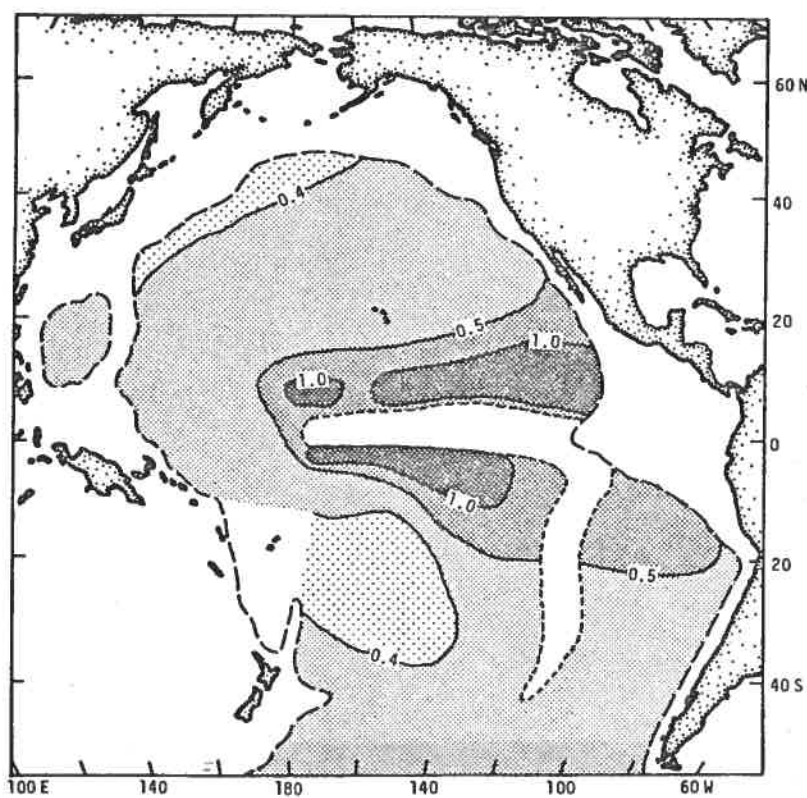


Figure 1. Copper content of Pacific deep-sea manganese nodules. The lines enclose locations of nodules containing more than stated copper concentrations. Lower grade nodules are found throughout the copper-rich areas. The numbers on lines are in weight percent.

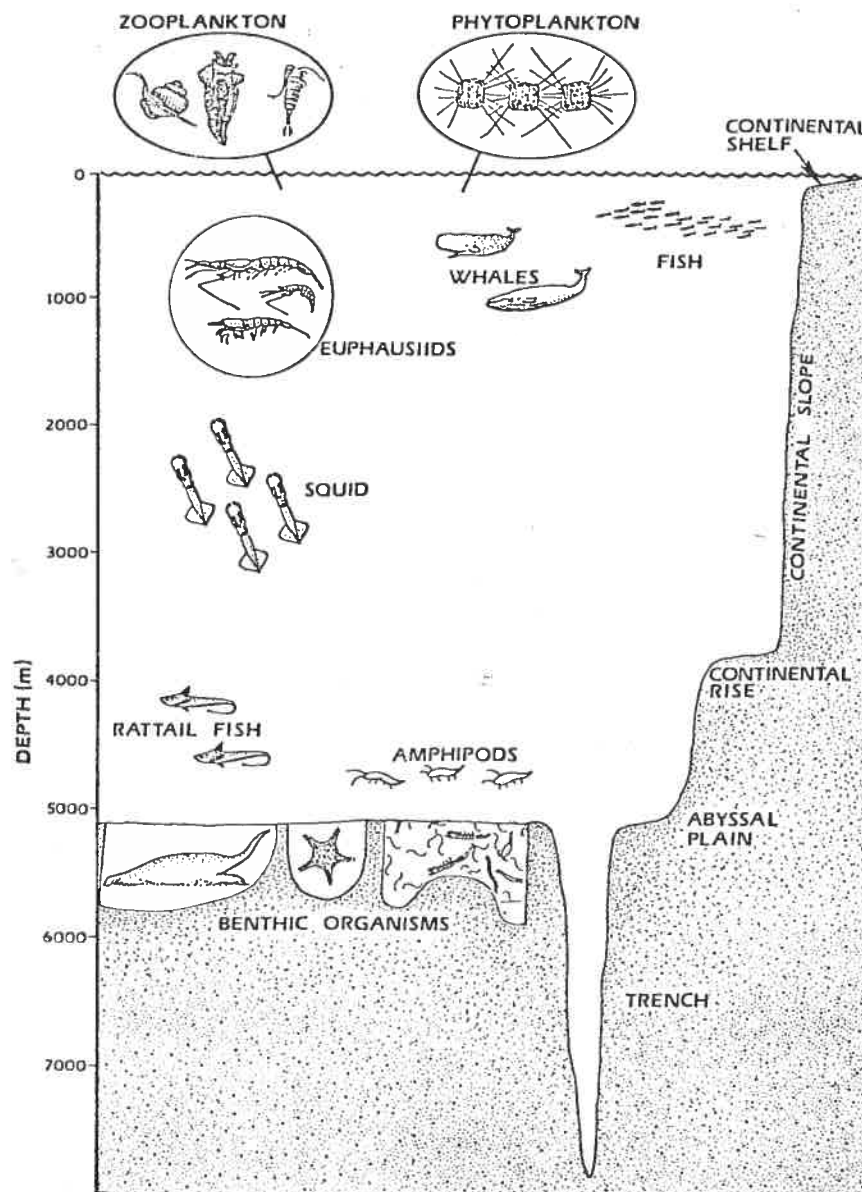


Figure 2. Representative oceanic biota (not drawn to scale).

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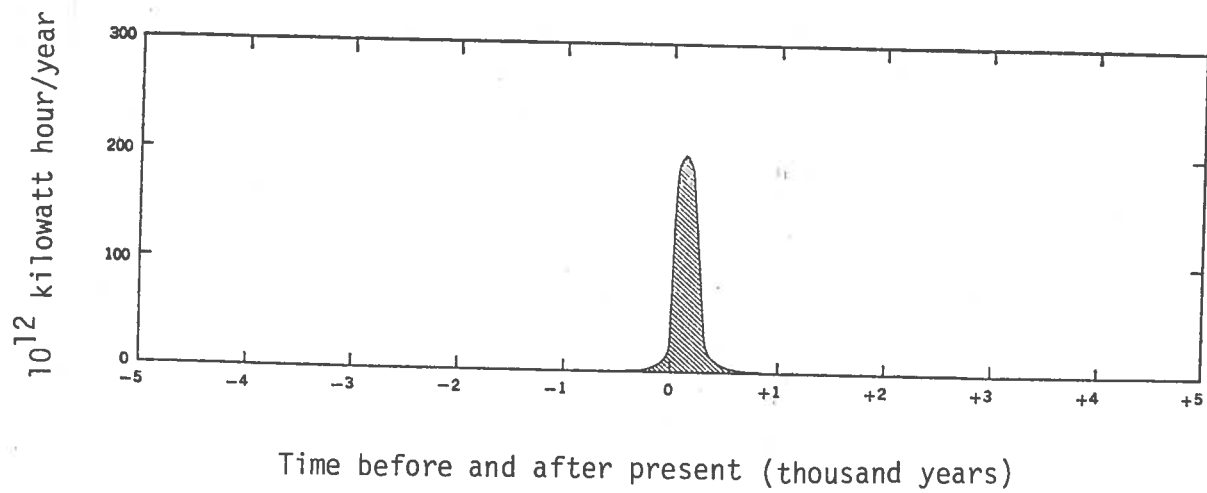


Figure 3. Epoch of fossil-fuel exploitation in perspective of human history from 5000 years in the past to 5000 years in the future.

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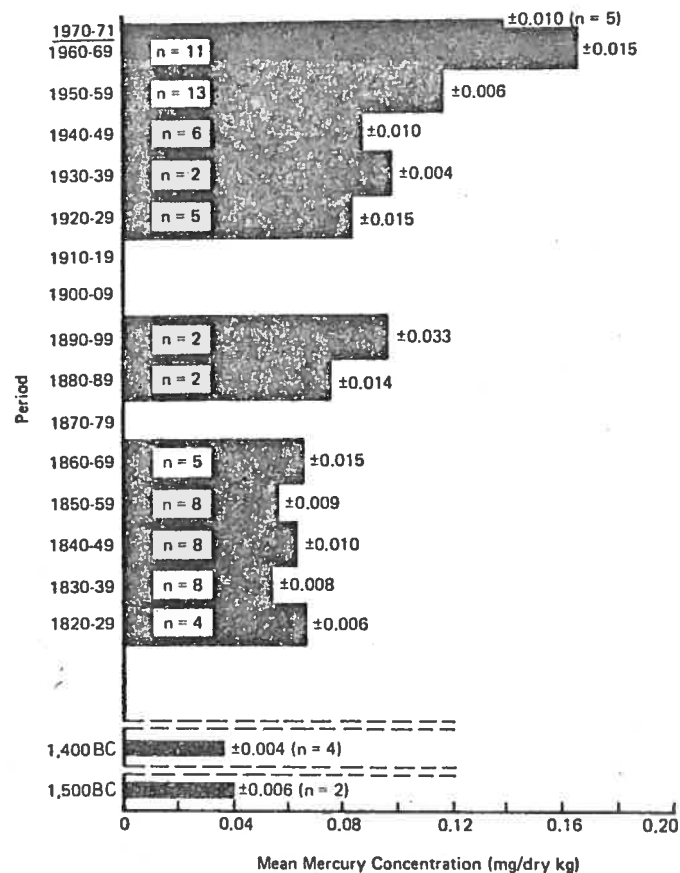


Figure 4. Mercury concentration in the sediment of Santa Barbara Basin off California. The water depth was 580 meters at where the samples were taken. The term n expresses the number of samples analyzed; the numbers after the symbol of  $\pm$  is the range of analytical variance (standard deviation).

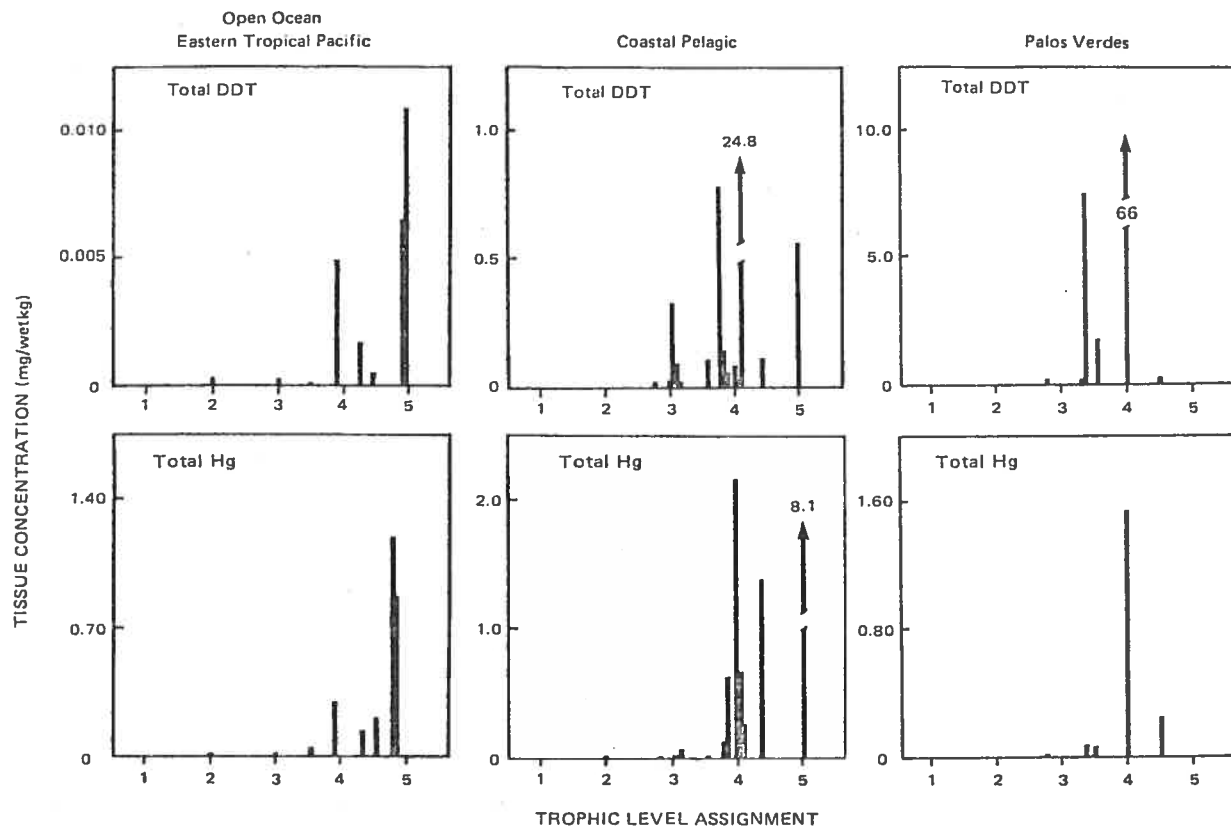


Figure 5. Two examples of contaminants (DDT and mercury) that increase with increasing trophic level. Species and their trophic level assignment are as follows: For the Open Ocean (eastern tropical Pacific), yellowfin tuna 4.82; silk shark 4.81; skipjack tuna 4.44; frigate tuna 3.92; squid 3.52; flying fish 3.00; zooplankton 2.00. For the Coastal Pelagic, white shark 5.02; mako shark 4.40; sea lion 4.02; swordfish 3.97; thresher shark 3.82; bonita 3.80; barracuda 3.74; Pacific mackerel 3.54; market squid 3.52; Pacific hake 3.09; jack mackerel 3.04; sardine 3.01; basking shark 3.00; blue whale 3.00; anchovy 2.82; zooplankton. For Palos Verdes, near Los Angeles, scorpion fish 4.53; spiny dogfish 4.16; Dover sole 3.52; white croaker 3.36; ridgeback prawn 3.33; mysids and decapods 2.78.



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Figure 6. The PCB concentration of  
Atlantic zooplankton, 1970 - 1972.

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Nature, the United Kingdom.

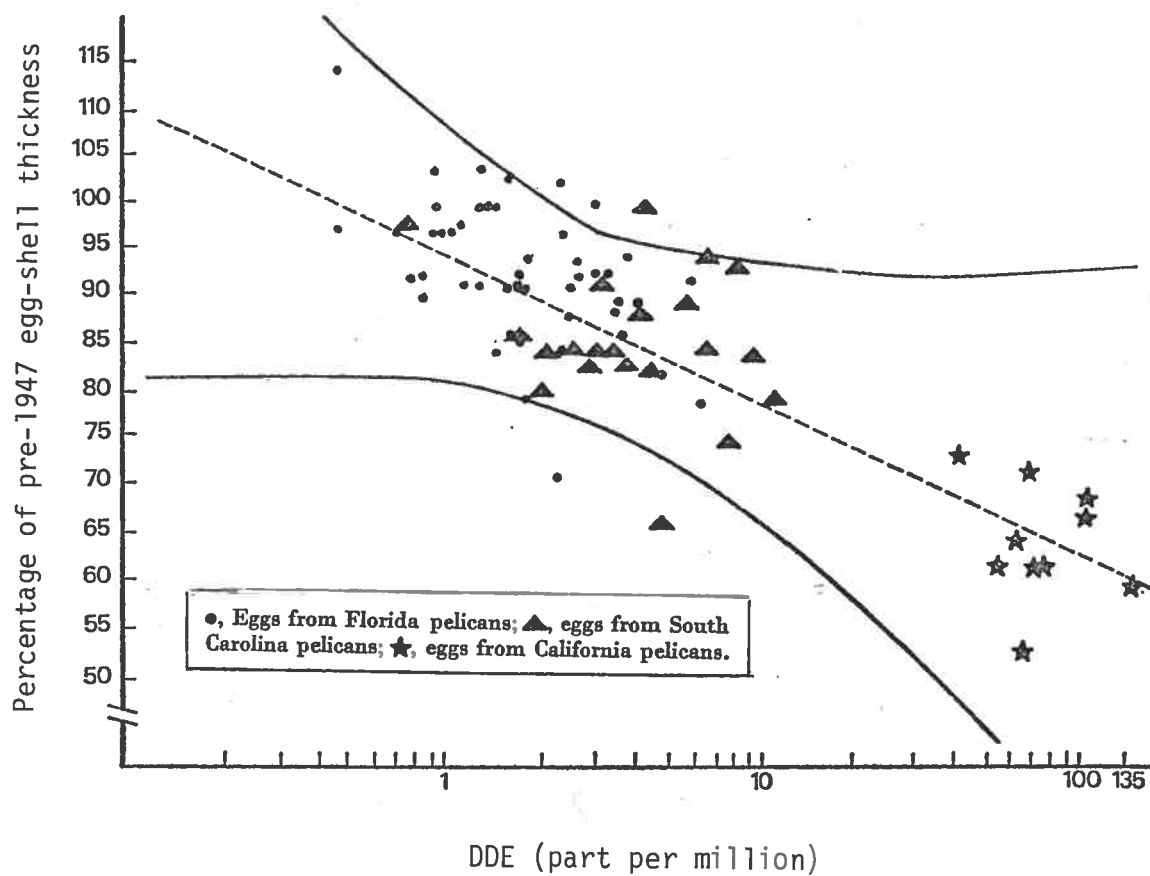


Figure 7. The relationship between egg-shell thinning and DDE in eighty brown pelican eggs. Solid lines represent 95 percent confidence limits.

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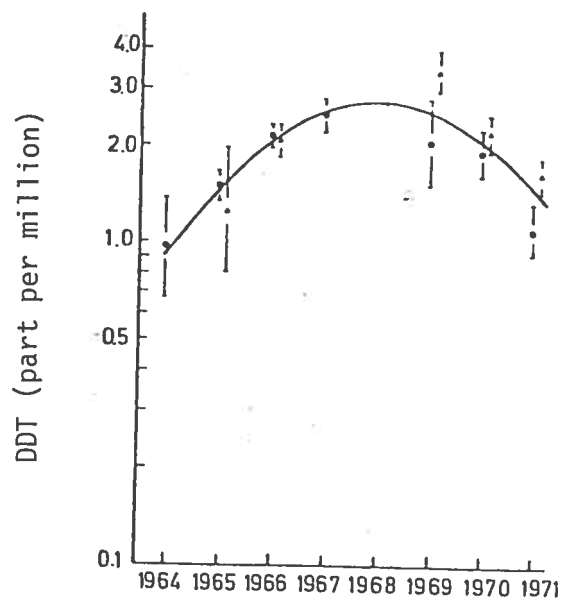


Figure 8. The DDT concentration in the eggs of shag at two British bird colonies located at Farne, Northumberland (shown by points) and Isle of May, Scotland (shown by triangles).

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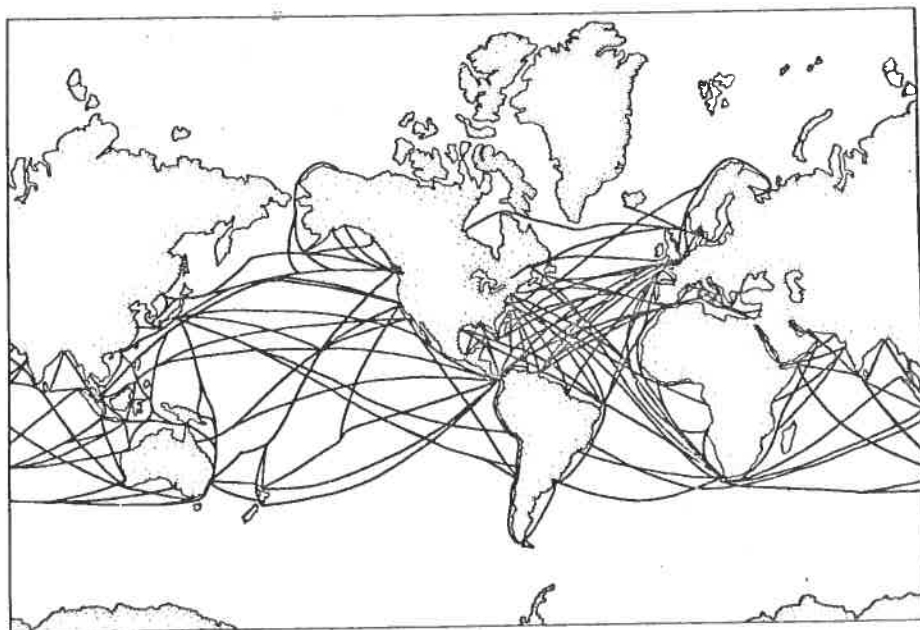


Figure 9. Major shipping lanes  
of the world.

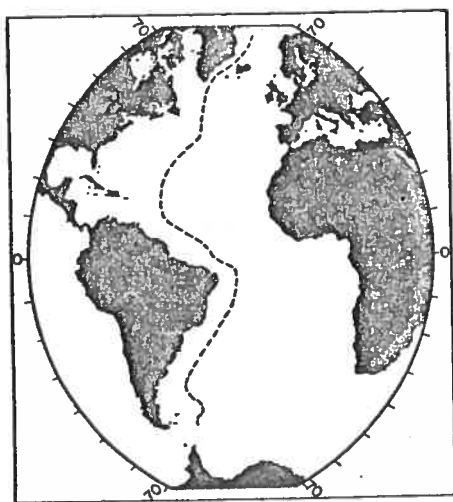
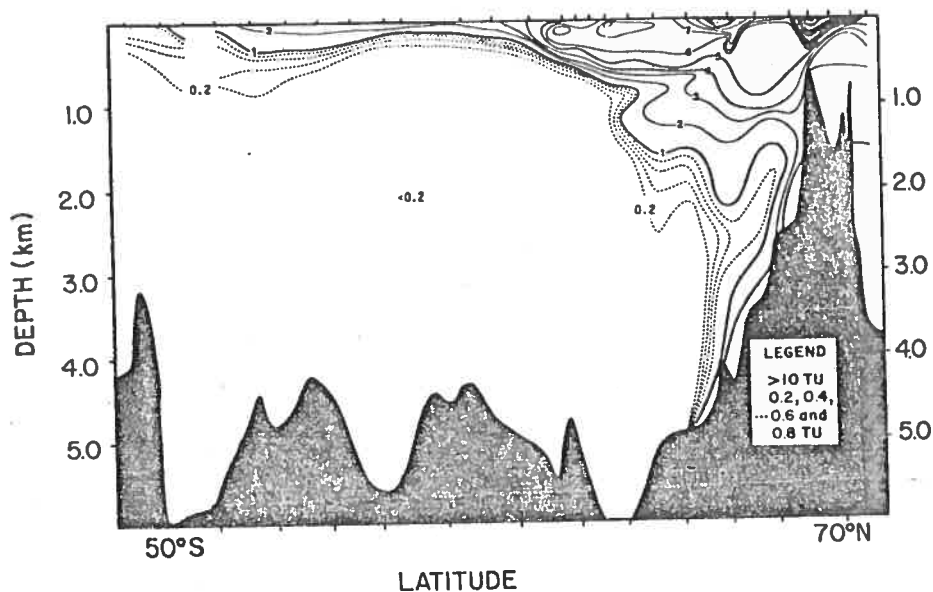


Figure 10. The radioactive hydrogen-3 intrusion into the deep North Atlantic water, 1972. The unit TU is the atom ratio of hydrogen-3 over hydrogen-1 (nonradioactive) multiplied by billion billion times ( $10^{18}$ ). The lower figure shows the sampling line. The locations of the sampling stations shown at the top of the figure.

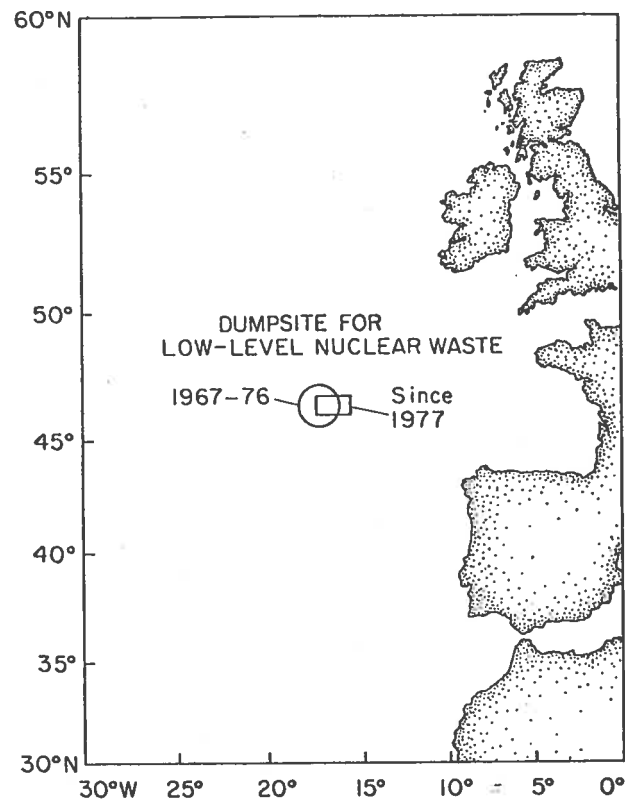


Figure 11. Northeastern Atlantic dumpsite for low-level radioactive wastes. It is used by several European member countries of the Nuclear Energy Agency within the Organization for Economic Corporation and Development.

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and Sons, New York.

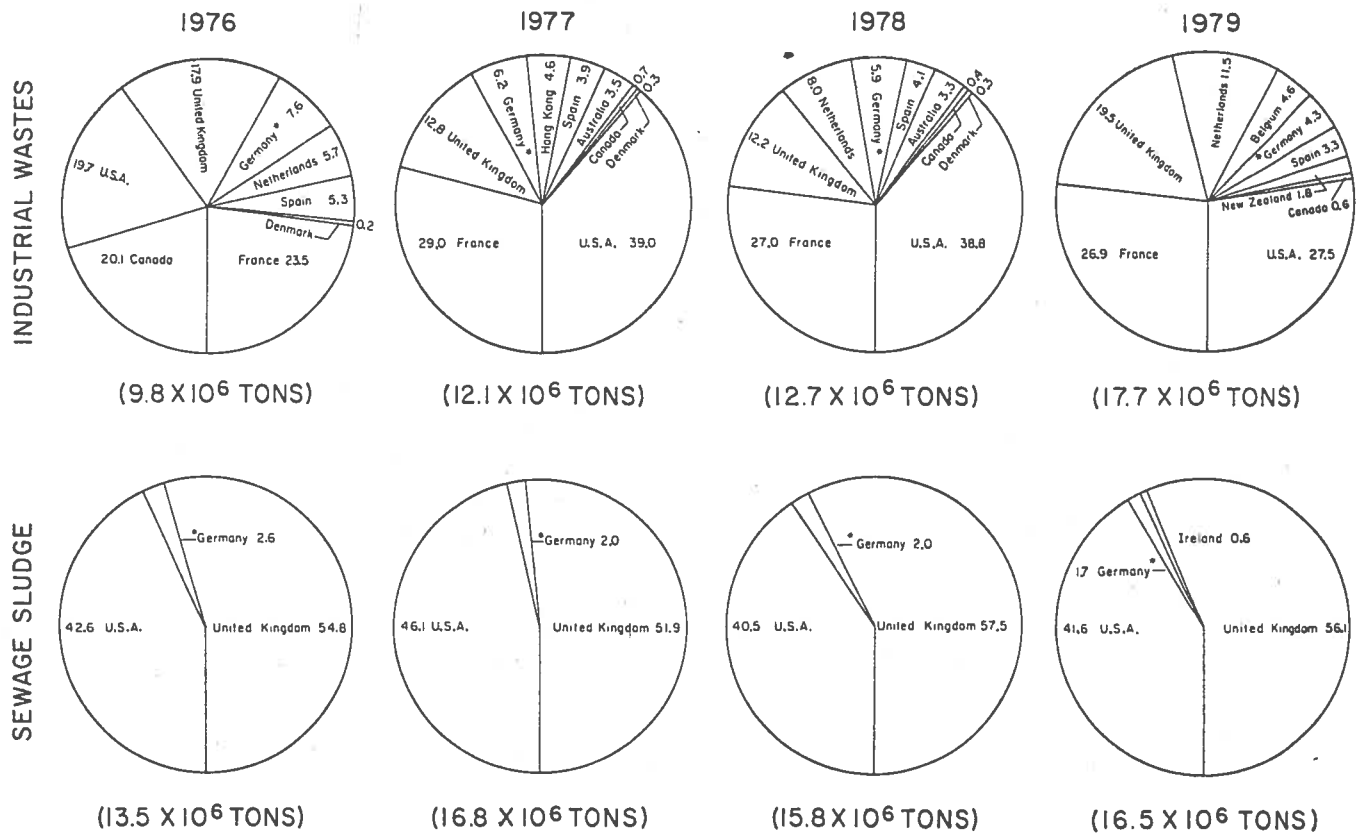


Figure 12. Percentage of the estimated tonnage of industrial and sewage wastes for ocean disposal (ship dumping). Germany\* is the Federal Republic of Germany.

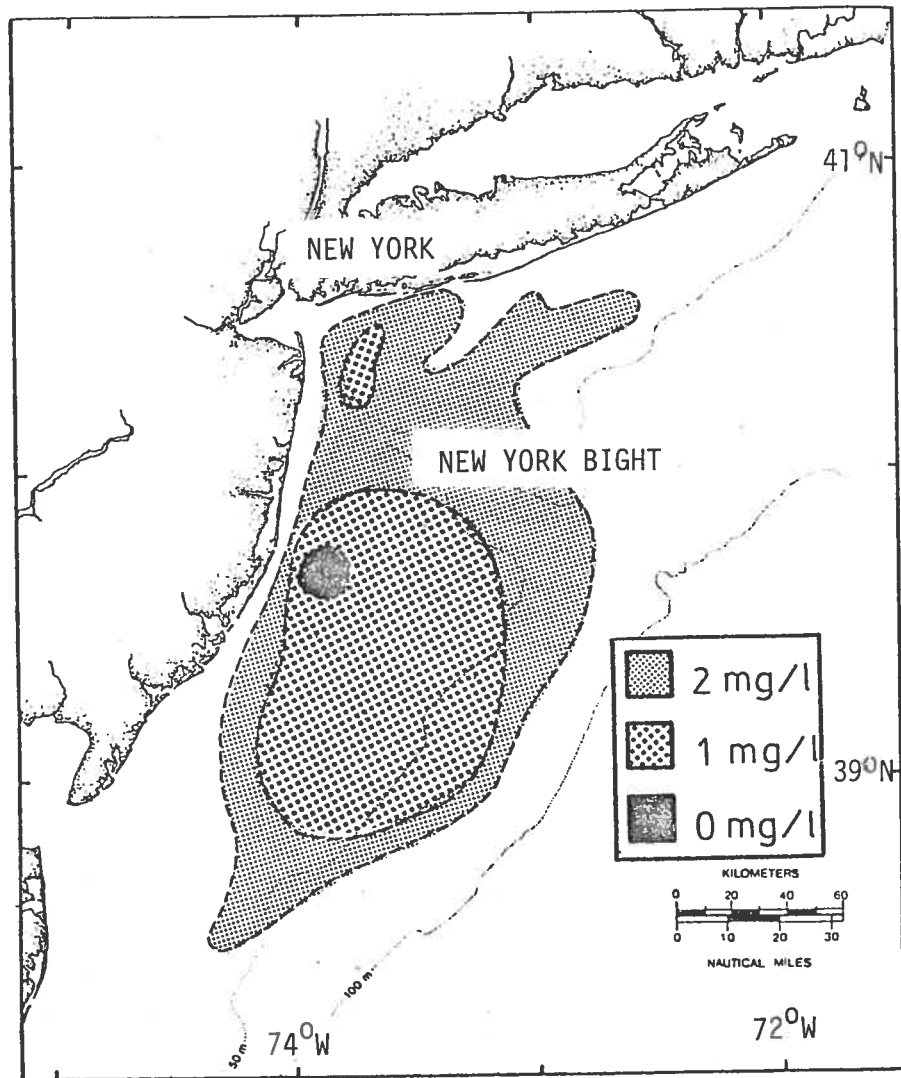


Figure 13. Dissolved oxygen distribution in bottom waters of the New York Bight, summer 1976.



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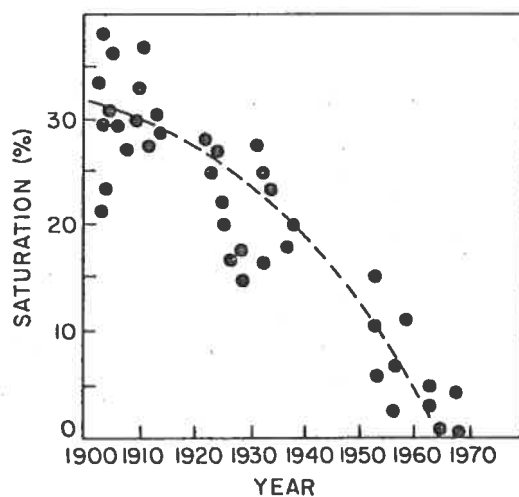


Figure 14. Decreasing concentration of dissolved oxygen, expressed as percent saturation with respect to the atmospheric oxygen content, at the Baltic Sea bottom in recent years.