Problems Ahead

<div style="text-align: right">**15**</div>

15.1 The Central Problem

For thousands of years, we humans have found ways to control our natural environment – using fire against the cold, building shelters against bad weather, and extracting sustenance from the biosphere on land and in the sea. All the way through this history, these activities kept increasing, especially in the last two centuries. Now we have to learn to cope with a new geologic force of planetary proportions – our own activities disturbing the "regular" course of events.

Prime examples of the impact of the new forces are found in the overexploitation of biosphere resources, such as fish and forests. ("Overexploitation" is *unsustainable*; that is, the annual harvest is greater than the annual addition to the resource and thus cuts into the potential harvest of future generations.) To this must be added climate modification and waste disposal. (Both items are of geologic interest. They exceed nature's ability to accommodate disturbance.) Efforts are underway to meet the challenges arising. On the whole, success in dealing with negative effects of human activities in anticipatory fashion has been very modest.

15.2 A Role for Marine Geologists

As mentioned in the preface, geologists do have a responsibility to bring basic knowledge and professional experience to the ongoing discussions. Quite commonly, the task of a marine geologist is simple enough: to show (i.e., offer evidence) that human activities have geologic consequences. This includes the fact that short-term activities have long-term consequences for climate change and other environmental conditions.

There are a few things marine geologists can contribute to current discussions, even though geologists might not be more adept at finding answers to the central questions arising than others pondering the matter.

From the marine record, we can certainly learn how the climate system has responded to past disturbances and how fast. True, it is likely that the system will respond differently in the future, since the ongoing global human disturbance is fast and unique. There is the danger of offering geologic palliatives for serious threats (such as trotting out a long time scale, involving thousands of years and more, when a short one of decades and centuries is more appropriate for human concerns at issue). In any case, however, what we know for sure is that if something happened it can indeed happen: no ad hoc dismissal of the evidence is possible.

Relevant discussions about geologic history presumably are not about remote possibilities on a million-year scale (the geologic time scale of Earth history) but about applicability of observations on a human time scale of a century and less. There is no question that the deep-sea record has more information in terms of sea-level change than do most other records. But the best resolution in deep-sea records of our extant planetary natural climate system (ice age climate fluctuations) is about one millennium (see Chap. 11). Information for events taking place on shorter time scales than millennial ones must be looked for in special locations or in certain organisms. Examples of such records are found in varved (=finely layered) sediments or in ice cores or in growth rings of trees or in various long-lived marine organisms, including certain corals. Unfortunately, organisms can engage in biased reporting, discriminating against reporting "bad" conditions by ceasing to grow, seasonally or interannually. Also, reporting organisms can adapt to a changing environment, thus reducing the range of the physical information recorded. Ice core records obviously are limited by the location they report on.

Records on changes in the frequency of large storms and of large eruptions also may conceivably become available for examination or verification of relevant assertions. (The ones whose assertions are being examined might consider that the

examiners, while skeptical, take the assertions seriously enough to check them against history).

15.3   The Seafloor as Waste Receptacle

15.3.1 Humans as a Sediment Source

One of the oldest signs of human impact, one may assume, is the increased delivery of sediments to estuaries and harbors within the Holocene. The increase is caused by intensification of erosion on land from agriculture and from deforestation. Basically, a natural growth of erosion has a similar effect: an acceleration of the filling in of estuaries and of affected lagoons. By far most of the increase in erosion observed for recent geologic time (on the million-year scale) is natural: the action of ice on land is ultimately responsible. But some of the rise in erosion (the one from agriculture and deforestation, beginning a few thousand years ago) is of human origin. Some of the new erosion provides "extra" sediment to the seafloor, beyond the natural supply. One might classify it as waste. Some of it definitely indeed *is* waste. Where waste increases nutrient input, it may result in "eutrophication" stimulating algal growth, including harmful algal blooms.

15.3.2 Increasing Waste from Cities and from Agriculture

Coastal cities and agriculture have contributed nutrients to the sea for centuries, stimulating algal growth in places, some harmful. This process has recently greatly accelerated owing to population growth and the increased production of waste and fertilizer. In places where waste amounts are sufficiently large and water bodies are restricted, considerable damage can ensue from waste disposal and fertilizer runoff both in terms of impact on tourism and regarding biological resources. Some effects are readily seen on the seafloor, in the changes wrought in benthic biota (Fig. 15.1). Difficulties in separating natural from human causes do not constitute evidence, of course, that human causes are unimportant. That sort of conclusion (not uncommon) ignores the rules of logic.

In recent decades, the amount of waste delivered by cities to the adjacent sea has increased by leaps and bounds, and the sites of deposition have expanded correspondingly. Negative effects include dangerous levels of disease-causing microbes and blooms of harmful phytoplankton. Although many of the effects observed concern biology in the water, the seafloor is not exempt from the untoward consequences of the release of industrial pollution into the sea. The waste causing special concern does involve biology: it includes substances that tend to accumulate along the food chain, with organisms feeding
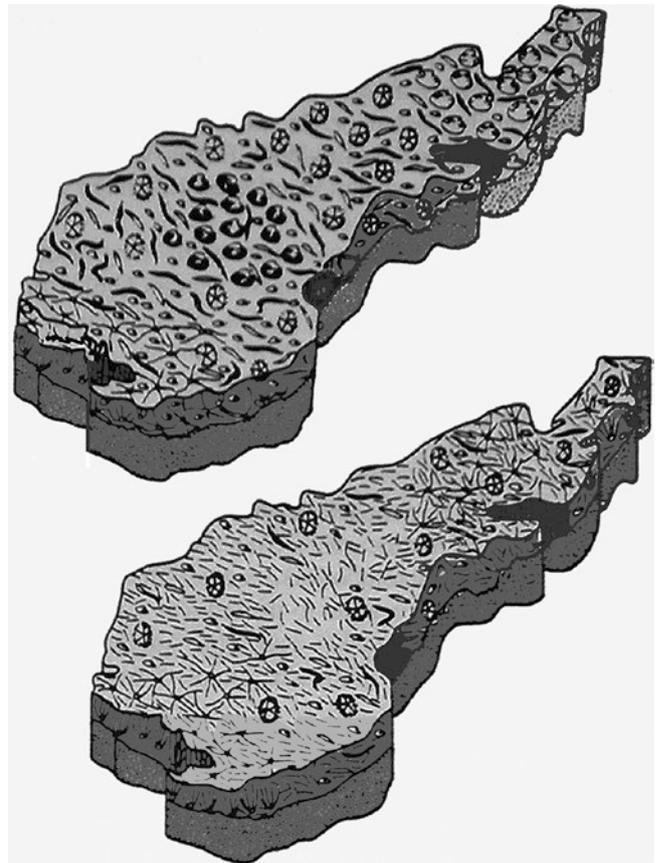

Fig. 15.1   Biota on the seafloor as indicators of environmental health in the North Sea (Dogger Bank). Mussels and sea urchins were replaced by brittle stars and worms in the time interval shown, suggesting a drop in oxygen levels and an increase in nutrient supply (Courtesy J. Lohse, modified for clarity. For the original drawing see J. Lohse et al., 1989, Die Geowissenschaften 7.6, 155)

at a high trophic level on the seafloor becoming poison-bearers. Thus, in many cases, the biological amplification affects the quality of marine food consumed by people.

In contrast to agricultural effects and deforestation, which increase sediment supply to coastal areas, the building of large dams to intercept rivers for water and for hydropower presumably has the consequence of trapping sediment before it gets to the sea, starving beaches, and thus promoting the erosion of the coast. For example, the construction of the Aswan Dam in 1964 in the uplands of Egypt apparently has helped increase shoreward erosion around the Nile delta region.

15.3.3 Sewage and Sludge

Industry consumes energy and raw materials and produces waste as a by-product of its target output. Much of the waste, such as sewage sludge, may be relatively innocuous provided it is free of obnoxious substances such as certain met-

als, for example, or biocides, or disease-causing microbes. Portions of the sea at ocean margins are commonly rather limited regarding the waste they can absorb and process. This is especially true for estuaries and marginal basins. (Examples are readily found within the Baltic Sea, which is both a restricted basin and surrounded by large cities.) *Eutrophication* (reflected in algal blooms from overfertilization) is a common phenomenon in such places. Resulting sediments tend to be organic-rich, black, oxygen-poor, laminated, and stinky. Eutrophication commonly results in a shortage of oxygen due to greatly increased oxygen demand at the organic-rich seafloor. Such a shortage, sporadically exacerbated by varying climatic conditions, can produce massive fish kills.

Even "deep" dumping in the open sea and away from shelf areas of cities can be problematic. Disposal of municipal sewage sludge in moderately deep water as far as 185 km off the coast of New Jersey from 1986 to 1992 at a rate of 8–9 million wet tons per year affected benthic organisms some 2.5 km below the dumping site. It had been hoped that dispersal and dilution of sewage particles in shallow waters would prevent waste from entering the food web at such depths. In many coastal cities, seaside recreation is big business. Thus, the pressure for "clean" disposal of sewage and sludge can become intense. "Beach closed" signs obviously are highly unwelcome, especially if it results in turning away economically important tourists and thus hurts hotels and merchants.

15.3.4 Garbage in the Deep Sea

Not even the remote deep seafloor is exempt from the effects of pollution and human deposition, as is demonstrated by the "garbage patch" phenomenon in northern central gyres, referring to floating debris. Some of the material is bound to reach the seafloor, as well. Much of the material involved (plastics) excludes an origin from natural sources. Unfortunately, apparently the plastic involved is mostly long-lived. Numbers mentioned for the typical life span of this type of trash include decades, centuries, and even millennia. Actual experience and observation covers decades only, of course, so one is likely to obtain estimates of varying quality. Items resembling food, but largely worthless in terms of nutrition, interfere with the proper workings of the food chain, touching many animals in the sea, including (one suspects) benthic ones on the seafloor.

15.3.5 Hydrocarbon Pollution

Hydrocarbon pollution comes in two versions: (1) sporadic and intense, and (2) chronic. The first type is referred to as a spill (Chap. 14). It gets much media coverage. The second is background and attracts not much attention, but is nevertheless an extremely important hydrocarbon pollution source, receiving a steady input from shipping and unregulated boating. Other sources exist in various kinds of hydrocarbon-based travel, in drains, in dumping, and in the operation of offshore rigs. It is sometimes claimed that background input is much larger than either natural seeps or catastrophic spills. Although supporting information is not very precise, there may be truth in such claims, especially when referring to conditions of decades ago. Apparently, much background input actually involves natural seeps, which obviously cluster in oil-rich regions. Thus, some tar balls on the beaches of southern California may not originate from industrial activities but may reflect natural processes. That many tar balls are in fact of industrial origin is suggested by the timing of occurrence and sometimes is proven by chemical analysis.

Major spills commonly involve either blowout from wells under pressure or else the demise of oil-carrying vessels that run aground or collide with others. Acts of war may also play a role, as in the enormous Kuwaiti spills resulting from hostile activities, in 1991. A recent large pollution event in southern Californian oil country occurred at Santa Barbara, where a pipe broke (a pipe of Plains All American Pipeline) and spilled thousands of gallons of petroleum, some of which apparently ended up as tar balls contaminating beaches in Los Angeles County.

In reported cases of catastrophic spills, oil dispersed by seawater demonstrably damaged the environment, killing seabirds and mammals and other marine organisms, according to both marine scientists and media observers. Negative impacts are especially large nearshore, in estuaries, and in tidal wetlands. It commonly takes several years in the case of the largest spills till the system comes back to what may be considered "normal" (a state not commonly well defined, however).

15.3.6 Radioactive Pollution

One legacy of the time of nuclear testing in the middle of the twentieth century is known to every marine geologist: the human-made radiocarbon spike around 1963 that is obvious in records with annual resolution. It is commonly noted in records of the last several decades (e.g., in laminated sediments, in coral, and in large mollusk shells).

The massive release of radioactive substances to the atmosphere by the *Chernobyl* power plant, in 1986, provided a unique opportunity to study the pathways in the marine environment of a number of dangerous radionuclides. Results from such studies (e.g., trapping and coring in the Black Sea) suggest that many, perhaps most, of the metals involved (e.g., the notorious cesium-137; beta decay, half-life 30 years) are rapidly removed from surface waters and

transported to the seafloor within biogenic debris. Similar fortuitously benign removal has been observed off the US West Coast when studying the effluent from the Hanford reactor near the end of the Columbia River.

Problems of an entirely different order arise in connection with high-level radioactive waste from power plants (such as Cs-137 and Sr-90). Given that large amounts of such waste exist on land now in a few places, and given that they can pose a considerable hazard, the disposal of such materials through burial in the seafloor is an option that has received some discussion and study. One type of proposal envisions canisters of various shapes placed into deep-sea sediments (including spear-shaped ones to aid penetration). Geologic questions that must be considered are as follows: (1) How stable is the target area? Is there erosion or uplift or faulting going on in the area at issue? (2) What type of circulation will develop around the hot containers, and what will be the effect? (3) What types of reactions of the sequestered material might be expected and what are the implications for a lasting confinement? "Lasting confinement" may have to involve thousands of years (in the case of certain trans-uranium elements with long half-lives). Given that many civilizations and nations have a history measured in hundreds, not thousands of years, a task requiring monitoring of hazardous substances for time spans exceeding many centuries seems extraordinarily challenging.

15.3.7 Risk Assessment

Clearly, there are risks involved in using the seafloor as a waste receptacle, and it is desirable to assess such risks *before* starting the dumping. In any case, one would hope that existing (albeit unfortunate) instances of hazardous dumping are used to study the processes that determine the fate of the materials in question. These include *dispersion* of the substances and alteration through *chemical reactions.*

Dispersion is controlled by bioturbation, resuspension, and transport by currents. Chemical reactions on and within the sediment can change the toxicity of materials and the ease with which they migrate through the sediment or are taken up by organisms. A well-known example with dire consequences is the mobilization of mercury by *methylation* within anaerobic sediments. ("Methylation" here describes the chemical reaction binding mercury to methane.) Methyl-mercury is a potent neurotoxin. When present in the environment, it gets concentrated in marine food (fish, shellfish) up the food chain. Consuming the food causes *Minamata disease* if ingested in sufficient quantity. The disease (disorientation, loss of balance and of control of the body in general) is named after the bay in Japan where it struck in the middle of the twentieth century and up to around 1970, owing to release of mercury by local industry.

15.4   Climate Change and the Seafloor

15.4.1 Revelle's "Great Experiment"

Sometime in the middle of the last century, it was widely realized that the continued addition of carbon dioxide to the air from the burning of coal and petroleum would unavoidably affect climate in harmful ways. Global warming was anticipated even at the end of the nineteenth century already, but it was not necessarily seen as harmful at the time. Also, in the first half of the last century, it was still widely believed that the sea would take up the bulk of the gas, thus greatly slowing the greenhouse gas buildup in the atmosphere. The Californian marine geologist and oceanographer Roger R. D. Revelle (1909–1991; Scripps director from 1951 to 1964) was adamant in insisting that this is not necessarily so on the short time scale considered. The ocean is not an ideal agent mitigating effects of carbon dioxide release. For once it responds but slowly to any change in atmospheric concentration, owing to long mixing times. In addition, concerning carbon dioxide, the ocean's potential for chemical reaction (and hence uptake of carbon dioxide) is quite limited by the abundance and availability of carbonate ions. Also, the sea warms at the top, which slows vertical mixing and thus decreases the rate of uptake from the air of any gas during warming, not just the one (carbon dioxide) that promotes warming of the planet by absorbing heat radiation.

Revelle's 1957 pioneering article on the subject (written together with the Austrian-American physical chemist Hans Suess) emphasized the limiting chemistry of the relevant reactive species in the sea. His article contains the often-quoted phrase about the "great geophysical experiment" that is carried out by mankind by modifying the composition of the atmosphere in a fashion that could only be done once. Realizing a need for documentation, Revelle caused the Cal-Tech geochemist Charles D. Keeling (1928–2005) to come to Scripps, where Keeling began his famous series, documenting the inexorable rise of carbon dioxide in the atmosphere from one year to the next.

The addition of carbon dioxide increased atmospheric content roughly 0.5 percent per year after 1980 (when the concentration was 340 ppm). The concentration of carbon dioxide in the air is small, hence easily altered ("ppm" is "parts per million"). In 2015 a level of 400 ppm of CO_2 was reached. In the coming decades, it is expected by many observers, non-carbon energy use might well keep increasing, but the rise of CO_2 will continue unabated. The presence of "positive feedback" suggests that there may be a point when the melting of ice cannot be readily stopped by ceasing to release greenhouse gases. When the horse has left the barn, thus the popular wisdom, closing the barn door is not the answer.

Incidentally, the observed rise in carbon dioxide, a greenhouse gas, *must* result in global warming; discussion of this

fact is unnecessary since we are dealing with basic experimental physics. One *can* argue about delay and about feedback processes that affect the precise *amount and rate* of warming, but not about the basic principle. The warming presumably is enhanced by an increase in humidity in the lower atmosphere and by various albedo effects, largely "positive feedback" on the human time scale, that is, reinforcing the given change on the scale of decades and centuries (not actually a positive development, but one re-enforcing the initial disturbance, potentially rendering it dangerous). Milankovitch theory of the ice ages likewise invokes positive feedback, as we have seen (Chap. 11). In fact, his climate theory of the ice ages presumably works *because* it relies very heavily on albedo feedback in high latitudes.

Revelle's "experiment" implies global warming, since carbon dioxide is a greenhouse gas; that is, a gas hindering heat radiation back to space, a radiation that normally balances the energy received from the sun (Fig. 9.1). A warming has to occur if energy is suddenly prevented from leaving. A warming indeed has been observed within the last century, culminating in an unusually strong rise toward the end of it. The resulting shape of the temperature history resulted in the term "hockey-stick" graph. The significance of the "hockey stick" has been the subject of much heated discussion, not necessarily discussion aimed at improving understanding. Discussion has subsided since. Apparently the data base used by the professional climatologists who discovered the hockey-stick shape of recent temperature history is not a substantial problem. As expected, data centuries old and subject to interpretation are somewhat less trustworthy than more recent ones.

15.4.2 Time Scale Problems

Time scale problems are pervasive. For example, after the year 2000, apparently there was a puzzling occurrence of little or no rise in temperature for more than a decade despite a continuing rise of carbon dioxide. The concept of missing warming (if bolstered by evidence) suggests that background temperature variations (some conceivably not wholly natural but partly caused by global climate change) can be strong enough still to mask some of the climate change from excess carbon dioxide. What emerges most clearly from the various discussions is that the ongoing experiment noted by Revelle apparently has different messages for people with different backgrounds. The identification of trends is a difficult matter, especially when using data from short time scales. Regarding climate evidence from marine geology, most of its information applies to scales much longer than decades or even centuries. Geology is about Earth behavior and includes long time scales measured in millions of years. While the lessons learned from long time scales indeed are useful for many purposes, they are obviously difficult to apply to problems arising on short time scales.

15.4.3 Some Basic Considerations on Climate Change

The phenomenon of global warming, as mentioned, reflects an emerging imbalance between the energy coming to Earth from our central star and the energy leaving the planet. The two must balance if the temperature on Earth is to stay the same (Fig. 9.1). The planet must warm if the incoming solar heat increases too rapidly to be gotten rid of simultaneously, for example, by suddenly providing for additional obstacles to reradiation (such as excess greenhouse gases in the atmosphere). Certain sediments on the seafloor (laminated ones for recent changes) can be consulted for clues to the history of the planetary energy balance, as reflected in temperature variation. (Technically, the energy balance is usually referred to as "radiation balance.")

As far as is known, the incoming amount of heat from the sun is comparatively stable on a short time scale (a century or less), although satellite data do allow for small variations and there is an 11-year sunspot cycle that is relevant to discussions of solar variation. Solar input apparently varies on longer time scales as well, as inferred from anomalous radiocarbon fluctuations on a 1000-year scale and as implicit in Milankovitch theory, which addresses change on a multimillennial scale. Some have regarded a fuzzy 1.5 millennia cycle based on changing sedimentation as evidence for a longish solar cycle. However, the currently observed (fast) warming is ascribed by working climatologists mainly to the buildup of obstacles for reradiation to space, that is, to the rise in excess greenhouse gases, rather than a brightening of the comparatively steady sun. To repeat for clarity, according to many or most experts, the sun is *not* the main reason for currently observed warming. We should be able to measure a brightening in the sun and not have to rely on fuzzy sedimentary evidence for inferring change relevant to now occurring events.

Of course, the climate system of the planet, that is, the various interactions of the many factors involved in energy transformations on the surface of Earth, results in enormous complications (Fig. 15.2). One important complication, as mentioned, concerns transfer of information from one time scale to another. Also, plenty of difficulties arise when contemplating cooling and warming effects from changes in cloud cover, in any time scale. Thus, the underlying simplicity of the radiation balance tends to be obscured, and interpretations of changes in this balance are correspondingly difficult. Problems arising from uncertainties are the fundamental reason why some attack on the scientific consensus is unavoidable (and why the IPCC is reporting implications of scientific findings in terms of somewhat ill-defined probability rather than insisting on strict quantification). What we are quite sure of is that human-released excess carbon dioxide warms the planet – it would seem that everything else is open
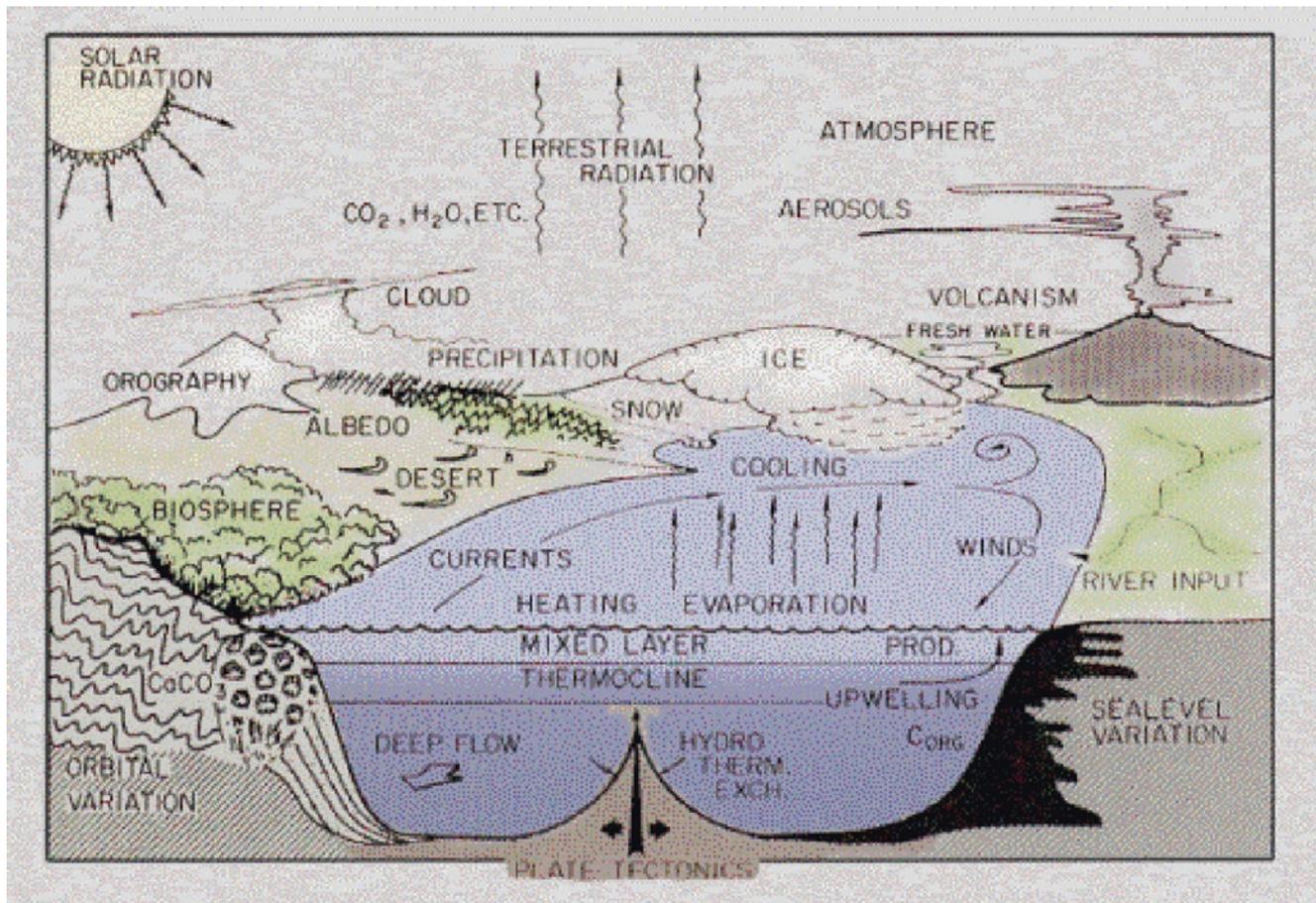
Fig. 15.2 Diagram depicting the major elements of the climate system in schematic fashion. Major sources of instability and uncertainty include clouds, seasonal variation, ice mass, volcanism, deep-water production, upwelling, volatile gases in the seafloor, and human activi- ties (Graph from W.H.B. and L.D. Labeyrie (eds.) 1987. Abrupt Climatic Change: Evidence and Implications. Reidel, Dordrecht. Color here added)

to discussion, especially information involving the precise path of future developments.

On occasion questions have been raised about the quality of mathematical modelling of climate change. We offer several comments regarding this much argued-over topic: (1) Granted that the climate system generated by feedback mechanisms active on several time scales is extremely complex, a mathematical treatment seems much preferable for producing estimates of future conditions to a nonmathematical seat-of-the-pants approach. (2) It seems quite obvious that a mathematical model cannot be more trustworthy than the rules of climate behavior that it assumes, and (3) those assumptions cannot be better than current understanding of the behavior of the various elements of the climate system in the time scales at issue. Large uncertainties persist both for long and for short scales. For example, there is the treatment of clouds, which can both cool and heat the area below them (by shading the ground or by sheltering it from loss of heat). Obviously it is of great interest which process – heating or cooling from clouds – is the stronger in any given situation

of a short time scale and also overall as a factor affecting latitudinal zonation, on a geological scale. The question is difficult to answer. (4) On a short time scale, when geologic hazards threaten, we must deal with risk and uncertainty, rather than assuming that a lack of certainty implies safety. As the late climatologist Steve Schneider said to one of us: "Uncertainty cuts both ways: the outcome of the (Revelle) experiment could be worse than anticipated." Schneider's comments are a reminder that this particular experiment (of releasing carbon dioxide in large amounts) is not suited for gambling. In other words, throwing doubt on expert opinion is dangerous in this case.

15.4.4 Abbreviating the List of Anticipated Calamities

The list of possible impacts from a general large warming is quite long and frightening. The rise of sea level is comparably easy to conceptualize and measure. Among other things, the

conversion of ice on land to water in the sea raises sea level, with many dire consequences for people. To be sure, there are many other potentially very undesirable consequences of global warming. Thus, the planetary heating presumably interferes with ocean circulation and alters the wind system, causing a host of changes in productivity and other environmental processes. Potentially there also are grim corollaries for storm activity and rainfall distributions. Concerning the chemistry of the sea, there is the (observed) issue of an expansion of the anoxic zone, presumably mainly reflecting nutrient pollution, but exacerbated by decreased solubility of oxygen in warming seawater. Also, there is the *acidification* of seawater resulting from the uptake of carbon dioxide by the surface waters of the ocean. Marine geologists will increasingly be faced with such changes as seen within the composition of sediments on the seafloor and within the calcareous skeletal structures built by corals and by many mollusks.

Regarding biodiversity, any rapid climate change results in vast numbers of organisms poorly adapted to the new environment and thus subject to a culling that may result in mass extinction. Much of the recovery of biodiversity from a large disturbance seems to involve a geologic time scale (thousands and even millions of years, rather than decades or centuries). Concerning human well-being, anticipated changes of biodiversity on a human time scale have implications that are commonly quite unwelcome. The list is long and calamitous. Unfortunately, feedbacks in climate change seem to be largely positive on a human time scale over a wide range of change, while any negative feedback (system response favoring a return toward initial conditions) may reside in time scales too long for comfort. It is possible that both positive and negative feedbacks are always present but are operating at entirely different rates. If so, confusion of the pertinent issues would be expected.

15.4.5 Why Not Simply Stop Digging?

A well-known proverb advises to stop digging whenever you find yourself in a hole of your making. So, what prevents us from ceasing to add greenhouse gas to the atmosphere? The answer is rather straightforward: an overwhelming and urgent demand for energy and a traditional view of how economic issues are best approached. In a nutshell, the level of public worry about the potentially terrible effects of excess greenhouse gases in the climate system is as yet difficult to translate into political action. One may deplore the underlying weighting of arguments. However, perception can create a reality of sorts. It may be based on nonscientific reasoning, but it still must be dealt with. At this point, it is not clear where usable answers for meeting the conundrum will emerge. In the meantime, sea level is rising distinctly and observably. It is a relatively simple and measurable process.

15.4.6 Rates of Sea-Level Rise on a Short to Intermediate Time Scale

Sea level is bound to rise as a result of a general warming, no matter what the cause of the warming. A rise of between 150 and 200 mm characterized the twentieth century. It was detected despite all local complications, which caused much uncertainty before the arrival of satellites. The rise may have accelerated in recent years. One expert reconstruction, for example, suggested a global rise of 40 mm in the first decade of the twenty-first century. If this satellite-based value is correct, one can then expect a rise of nearly one half of a meter by the end of the century using straight extrapolation. Given the reality of continuing increase of input of carbon dioxide and other greenhouse gases, it seems more likely that sea-level rise will accelerate some more. The result will be, one assumes, a steering of the system toward a rate of ice melting similar to the one that prevailed at the end of the last ice age 10,000 years ago. At that time sea level rose at an average rate greater than 1 m per century (1000 mm per 100 years) for several thousand years.

Sea-level rise is likely to impact millions, since the coast is a popular site for human settlement, judging from regional conditions (Fig. 15.3). Already one fourth of the average rise during deglaciation (i.e., about 30 mm per decade) can result in enormous damage given enough time, including making traditional housing and agriculture obsolete near the coast.

At the present time, most of the sea-level rise apparently is from thermal expansion. However, the potential for the contribution from polar ice is very large indeed: melting Greenland ice can yield around 7 m of sea-level rise and melting the ice on Antarctica ten times that. The mass (and hence the potential contribution) of the rather vulnerable West Antarctic ice is roughly equal to that of Greenland ice. East Antarctica has ten times that amount. The total available

Fig. 15.3 Coastal settlement patterns, San Diego between La Jolla (N) and Ocean Beach(S) (Photo W.H.B)

ice mass that can be melted is roughly 80 m – approaching the amount of ice involved in the terminal melting event of the last ice age (ca. 125 m) and presumably repeating some of the ice and meltwater behavior at that time. The last melting event (and analogous earlier ones) may have lessons concerning the way polar ice melts. Ice responds to warming, but this is only one of the factors, there being a host of positive feedbacks on melting, including sea-level rise itself.

15.4.7 Rates of Sea-Level Rise: The SPECMAP Evidence

During the last major melting ending the last ice age, an average rise of more than 1 m per century was maintained for many tens of centuries (roughly 120 m in 10,000 years). This particular information has been available for several decades (Fig. 6.5). We are confident since the 1960s that sea level rose by more than 100 m during somewhat less than 10,000 years in the last deglaciation event. Since at least in the 1970s, it is thought that deglaciation was strongly pulsed and that the average rise rate was exceeded substantially on occasion. A rise of a meter per century (1 cm per year) or slightly more simply was nothing unusual during the time of major melting. It was close to average for thousands of years. Analysis of data in the literature produced in the 1980s readily confirms it. A prominent curve on sea-level positions suitable for this type of analysis is the "SPECMAP" standard of J. Imbrie et al., published in 1984.

The "SPECMAP" oxygen isotope series (purportedly depicting the history of the last third of the Pleistocene) can be converted to sea-level change abundances by assuming a total change in sea level of 120 m during the last deglaciation and matching this change to the corresponding one observed in the oxygen isotopes. One fundamental assumption in this procedure is somewhat questionable: It is that temperature effects do not matter in the conversion, because they tend to run parallel to ice mass. The SPECMAP data are listed back to 782,000 years ago in 2000-year steps in the data source. They are greatly smoothed. The series, it turns out, is usable to about 650,000 years B.P. Maximum rise rates in this exercise emerge at slightly higher than 1.5 m per century; that is, the "maximum" is fairly close to the average rise of sea level, for millennia.

It should be pointed out that the period before 450,000 years contains sea-level events that apparently have causes different from those of later events, making the entire set analyzed inhomogeneous. This may not be relevant for the comparison with the modern sea-level story, however, there being no analogs to modern events in any case. Other problems exist also. For example, there is a surprising lack of information on the last 8000 years or so in the SPECMAP data, perhaps an indication of loss of surface sediment during

(piston-) coring. Any Holocene gap on recording historical changes during the last deglaciation would have an effect on calculated sea-level distributions: Closing a recording gap of several thousand years in the Holocene with available data (the series purportedly starts at zero age going backward) would introduce a spurious sea-level rise into the Holocene and decrease the overall rise during the last deglaciation correspondingly.

The data suggest, that a substantial buildup of ice is what is most commonly seen in this record on a millennial scale, but that the ice can melt sporadically unexpectedly fast (also see Fig. 6.5). Analysis of other isotopic ice age data, less smoothed, indicates that a rise close to 3 m per century, while definitely not common, can be seen on occasion on a millennium scale. Actual century-scale changes presumably occasionally substantially exceeded this rate, which only represents an average valid for a millennium that was especially prolific regarding the contribution of meltwater.

15.4.8 Neogene-Type Ice Masses

Of course, great caution is advisable when studying the ice ages for lessons applicable to the ongoing warming. We study a system that has ice at both poles and changes rather slowly (the ice age system) to better understand one that is on the way to become entirely lopsided, with very little ice on the northern hemisphere, a system much like the one in much of Neogene time (Fig. 15.4). According to the late climatologist H. Flohn (Bonn), the asymmetry is bound to increase in the future and possibly quite fast.

What then can we learn for the future from studying the ice-age past of the planet?

We can certainly learn much about the behavior of the climate system in general. But application of particular insights to prediction of future developments is heavily constrained. What emerges as a strong suggestion is that ice is likely to display unstable behavior (in melting unexpectedly fast and sporadically) and any regular (linear or nonlinear) extrapolation of past sea-level rise to the future is therefore
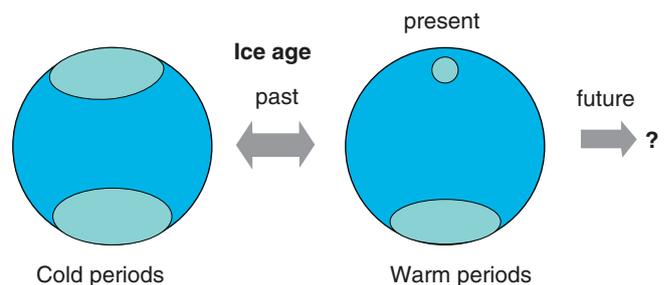

Fig. 15.4 Schematic concerning the relevancy of ice-age climate to global warming, according to concepts of the late H. Flohn (erstwhile meteorologist at the University of Bonn)

tagged with major uncertainty. Uncertainty need not entail lack of action (it does not when contemplating military threats). However, uncertainty encourages a reliance on personal opinion and unavoidably affects political perception and international negotiations. Asking a medical doctor for proof for his assertion that certain behavior may result in major problems is rather dangerous, of course. Proof may be too late to be useful.

What the marine record suggests is that sea level will keep rising thanks to positive feedback once the process has entered the cm-per-year magnitude (the typical rate of natural deglaciation). To what degree this insight applies to current events is uncertain. It is unlikely to be entirely irrelevant, however. We may quite literally approach sea-level rise rates last seen during the last deglaciation. The soaking up of meltwater by parched land (as suggested by some NASA scientists) perhaps brings some temporary relief, but is likely to end up as another irrelevant discussion topic as far as the millennial time scale.

15.5   The Carbon Cycle Modified

15.5.1   Relevance of the Carbon System

The science of the carbon cycle is central to discussions in the present text for several reasons. One is that the largest of the highly active carbon reservoirs is in the sea (total dissolved inorganic carbon is about 60 times atmospheric content). Also, some of the very large (and much less active) geological reservoirs are made up of marine carbonates, of marine petroleum-type substances, and of carbon-bearing gases of marine origin (as discussed in the previous chapters). The scientific discipline relevant to carbon cycling belongs to the discipline of biogeochemistry. Its chief ingredients are in the name: biology, geology, chemistry.

On the whole, the largest reservoirs are part of the multi-million-year cycle, while smaller but highly active ones help define the short-term cycles (including decadal ones). The largest marine reservoir by far is part of the crust of the planet: it is in the marine carbonates on land and in its crust and in the oozes and chalks of the seafloor. The reservoir has more than a hundred thousand times the atmospheric carbon mass or "ACM." Organic carbon mass in marine sediments (e.g., petroleum and other hydrocarbon) occupies second place, as far as abundance of carbon (less than half of the amount of carbon in the carbonates). The next largest reservoirs, and quite relevant on scales of centuries to millions of years, are the amount of dissolved inorganic carbon in the sea (ca. 60 times ACM) and the dissolved marine organic carbon (less than one tenth of that). Soil organic carbon, forests, and peat are next (probably in that order), each being in a class with the atmospheric reservoir and highly relevant to

ongoing changes. The phytoplankton in the sea is a distinctly smaller reservoir, albeit a highly active one (i.e., it generates a large carbon flux compared with its size).

All reservoirs vary in tandem with changing environmental conditions, affecting geologic processes accordingly, for example, through deposition of carbonate and organic matter. Carbonate deposition affects, for instance, the building of continental margins and presumably can facilitate the motion of plates when entering the upper mantle. Organic matter deposition affects all aspects of the productivity of the sea, and hence the sea's biological and biogenic resources, and provides clues to marine evolution. Many carbon reservoir fluctuations are well known. Fluctuations of the atmospheric carbon dioxide gas content are particularly well studied for the ice ages thanks to the work begun in the laboratories of French and Swiss geophysicists (Jean-Claude Lorius, Grenoble, and the late Hans Oeschger, Bern). A substantial portion of Milankovitch-scale climate variation presumably is attributable to the well-tracked (but poorly explained) carbon dioxide variations that closely follow orbital forcing. Any attempt at such explanation brings us welcome additional familiarity with the controls on atmospheric carbon dioxide, thus teaching us important aspects about Revelle's great experiment.

15.5.2   "Sensitivity" to a Doubling of Carbon Dioxide and "Safe" Levels

It has been said, correctly, that in essence we humans are returning to the environment, on the time scale of a century, the carbon that was stored in coal and oil over hundreds of millions of years (a factor of several million in terms of applicable rates). This is the essence of the "great experiment" referred to by R. Revelle. We are now cognizant of the difficulties arising, an alarm having been sounded by a number of perceptive pioneers (including Revelle) and by the IPCC founder and his organization (the Intergovernmental Panel on Climate Change). The founder was the Swedish meteorologist and carbon-biogeochemist Bert Bolin (1925–2007) whose concern was to get reliable information on climate change to the public and to decision makers.

A doubling of background atmospheric carbon content is expected within the present century by many expert climatologists. Will marine geologists recognize the event in the record when it happens? At this time, we cannot possibly know.

Many or most climatologists put the "sensitivity" of the climate system (warming from a doubling of carbon dioxide) in the range between 2 and 3 °C (4–6 °F). However, large uncertainties exist, resulting in about a factor of two on the central estimate (2.5 °C for a doubling of CO_2). Because of the gaps in knowledge exemplified by the uncertainty regarding "sensitivity," it is futile to assign the word "safe" to the atmospheric content of carbon dioxide at any level above 300 ppm (the one

that worked for thousands of years). Time scales matter, and a "sensitivity" established for one scale is not necessarily valid for another. Our life spans invite us to emphasize short time scales of a century or less, but the long scales are very real for ecology and evolution, that is, for life on the planet.

15.5.3 Possible Lessons from the Late Neogene Changes in Marine Productivity

It appears that anything that affects wind velocity will also affect the productivity of the sea. Wind lives off temperature gradients. Thus, it would seem, a general warming more intense in high latitudes than in the tropics, by reducing the planetary temperature gradient, will eventually slow surface circulation and the productivity-enhancing zonal processes around the gyre margins. (The well-behaved gyres presumably are replaced with much less steady and sporadically active currents.) The time scale of the hypothesized processes involved, however, is not well constrained from marine geological insights. Observations of the California Current suggest that its productivity has been relatively low for decades already. The mechanism or mechanisms responsible for productivity and its collapse are poorly known and may be creating but a temporary anomaly, although a link to global warming is quite possible, perhaps even likely.

From marine geological studies of drilled Neogene sediments, we know that coastal upwelling started in earnest at the end of the middle Miocene, about 10 million years ago. Presumably, general cooling at the time fostered strength and zonal character of the wind field and thus enhanced mixing and currents linked to marine production. As soon as snow formed, it was able to affect seasonal albedo contrast, which probably affected upwelling in ways that boosted productivity (by increasing seasonal change and by alteration of mixing and stratification sequences). If so, a reverse development (from a general warming) of a reduction of snow and seasonal contrast may result in a reduction of marine productivity.

15.5.4 "Engineering Fixes"

The likely outcome of doing nothing or very little now to address the growing concerns regarding the problem of planetary warming will be a call for "engineering fixes," if and when problems become hard to deal with. Commonly such "fixes" are planned to reduce incoming solar energy by shading Earth's surface in one way or another or by facilitating the rejection of incoming energy by increasing planetary albedo. One alternative to shading and albedo manipulation is the reduction of greenhouse gas in the atmosphere. In essence, this would be an attempt to remedy the missed opportunity to restrict input of the greenhouse gas carbon

dioxide to a supportable level in the first place. One problem would be that past damage may be irreversible.

The process of mentally preparing for emergency action has begun, at least among many climate scientists. (Some "business-as-usual" people hardly foresee a problem). What can marine geologists contribute? Like other scientists, they can examine proposed "fixes" and point out possible unintended consequences for the manipulation of Earth systems including climate. Unintended consequences (by definition) are likely to result from poorly understood processes. Attention to factual history will be useful. Marine records documenting changes on short time scales do exist, as illustrated in the next section in this chapter. Their detailed study is only a few decades old, however, and they have to deal with the full complexity of the climate system. Insights are correspondingly limited and may not apply to the evaluation of any planned "engineering fixes." In a rapidly changing system such as ours, the challenge to identify those elements of the system studied that can be modified in satisfactory ways to provide "fixes" is likely to be enormous. *Caveat emptor.*

Again, a marine recording device appropriate for keeping track of millennial change is an unlikely candidate for tackling urgent problems arising on time scales with much higher resolution than ice ages. Ice as a recorder avoids many of the problems common in marine recording and may be more promising than marine sediments or records from marine biology. But ice may not turn out to be an ideal substitute for the marine record. On a warming planet, useful information from sediment stacks of ice comes from ever higher latitudes (or ever higher elevations). What will likely be missing is a reliable way of finding the implications of observed high-latitude recordings for low latitude systems (impacting millions) at a time when the systems are undergoing rapid and poorly understood changes. Again, to apply partial knowledge to extant problems (as may be proposed) may invite much-feared types of unforeseen consequences.

15.6 Short-Term Climate Change in the Marine Record

15.6.1 Varved Sediments

Finely layered marine sediments ("varves") deposited on the seafloor in anoxic environments and thus not stirred by burrowing organisms can deliver information on changes relevant for short time scales. Such sediments can be used to reconstruct historical trends on the scale of decades and centuries and to check for short-term periodicity in depositional sequences (e.g., such as the 11-year solar cycle). Also available for such checks are coral records (Fig. 8.4). As a general rule, one finds that short time scales tend to focus on local information; that is, the long-term records tend to have globally valid information, while short-scale records may mainly address local change.
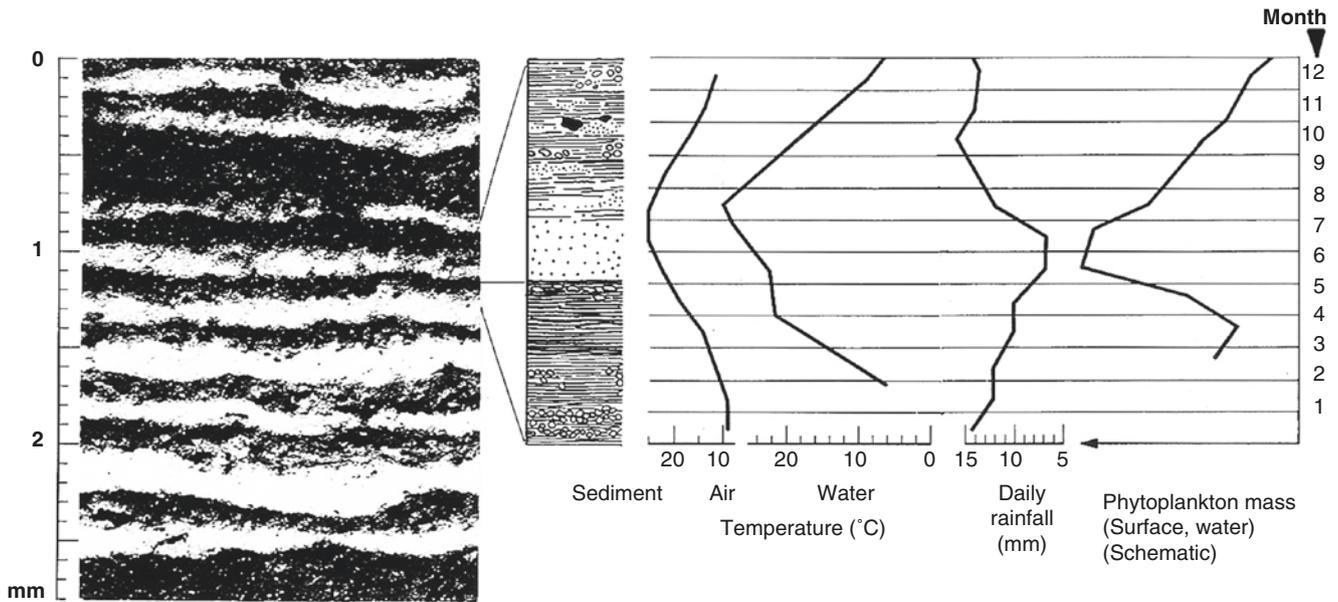
Fig. 15.5 Annual layers ("varves") in sediments in the Adriatic Sea. In the (simplified) microphotograph (*left*) one light-dark pair corresponds to 1 year. The light layers represent carbonate precipitation by phyto- plankton blooming early in summer (*right panel*). In fall and winter, rains bring terrigenous matter, which together with organic detritus pro- vides for dark colors (Photo E.S.)

Some of the earliest studies of marine "varved" deposits were done on the shelf in the Mediterranean Sea, in the bay next to Mljet Island, in the middle of the last century (Fig. 15.5). The nature of the varves as layers of alternating terrigenous and planktonic supply emerged at that time from a detailed study both of the laminae and the seasonally changing environment.

Detailed studies on marine varves in deep waters off California were carried out in the 1960s by the oceanographer and marine geochemist S. Calvert (then a graduate student and subsequently a postgraduate researcher at S.I.O.) with a focus on diatom deposition within the plankton layer (rather than carbonate as on the Mediterranean shelf in sediments studied earlier by E.S. and associates). Calvert found that dia- tom production, not volcanism, is responsible for high silica values within the varved sediments. The varves themselves represent a record of seasonal change in sedimentation.

15.6.2 Santa Barbara Basin: Recent Decades and Centuries

The basin off Santa Barbara is invaded by oxygen-poor water from the offshore oxygen minimum zone and made anaerobic by additional removal of oxygen from the overlying upwell- ing-type productivity in coastal waters. Its varved muds serve as a repository of detailed information about the history of the California Current in the region (Sect. 9.1.7). Within the time span of the last century, two items stand out (among several). One is a crash of diatom productivity in the early 1970s, dis- covered by C.B. Lange. It was followed several years later by partial recovery (Fig. 9.8). Another is the evidence for recent warming, from a change of foraminiferal content, beginning several decades ago and described by the marine biologist D.B. Field in his Ph.D. thesis (S.I.O., UCSD 2004).

The thickness of the varves cannot be determined pre- cisely, because the necessary correction for water content in the uppermost portion of a core is arbitrary. Unless a pre- cise value is desired, though, this is not a serious problem. That the recording sediment is changing on a short time scale is evident both in the thickness of varves and in their contents (such as the fish scale abundance studied by the late J.D. Isaacs and his colleague and erstwhile assistant, A. Soutar). Periodicity of deposition is evident in the various types of varve records. Periodicity is easily determined by applying Fourier analysis, but the cause or causes of cycles emerging remain poorly understood. One vexing problem is that the mix of cycles changes over the centuries, sometimes rather abruptly. The reason is not known. Another problem is that missing varves (e.g., from sheetlike slumping at the place of deposition, following earthquakes) apparently can provide for an incomplete record, difficult to recognize as such when counting varves, but emerging on detailed dating.

15.6.3 A Question Re Solar Cycles

A changing sun has been proposed by some as a source of variability of modern climate. The Swiss physicist Jürg Beer and some of his colleagues, for example, have ascer- tained that a large portion of the climate change of the last 150 years is owed to changes in solar brightness. An impor-

tant question arises: Can a variation of the solar "constant" (the energy input from the sun) be recognized in the marine geology record? A related question addresses the fuzziness of the evidence: how well should the solar cycles be defined, and how well should they be matched in the record before a finding of such cycles is considered significant for understanding climate change?

As an aside, the late climatologist Stephen Schneider (NCAR in Boulder and later Stanford University) pointed out to one of us that documenting past solar effects on climate does not bear importantly on the sun's potential influence on present or future climate change. The questions to a geologist faced with the record are most commonly about what happened, of course, not about what is happening or what is likely to happen.

We can be sure that certain solar cycles are real: the sunspot observations of the last 300 years (collected, e.g., by the Royal Astronomical Observatory in Belgium) as well as the historical aurora record collected by the historian D.J. Schove (St. David's College, UK), and published in the Geologische Rundschau in 1964, with more than 1000 years of observations, yield a strong cycle near 11.1 years when analyzed by Fourier's method. In the aurora record, one also finds a cycle near 205 years, presumably the so-called "Suess" Cycle, named after the late Austro-American physical chemist Hans Suess (S.I.O.). He reported the cycle from radiocarbon records in certain tree-ring sequences. The ca.-200-year solar cycle also is known as "de Vries" cycle, named after a meritorious pioneer Dutch solar astronomer. In contrast, the much cited ca.-80-year "Gleissberg" cycle is not readily seen when using mathematical analysis on reliable solar data. The suggestion is that while the "Suess" cycle and the "11-year" cycle indeed describe solar activity, the "Gleissberg" cycle describes something else, possibly linked to solar activity in poorly understood ways.

Apparently the sediment supply from the mountains and drylands in southern California is not particularly responsive to solar variation on the decade to century scale. In any case, none of the dominant cycles below three decades long (near 29, near 23.4, and near 7 years) seen in sediments of Santa Barbara Basin are obviously of solar origin. They do suggest, however, that the varve thicknesses are capable of reflecting decadal-scale cycles if they exist. As concerns the ca.-200-year cycle, the available data series was not long enough for testing the Suess proposition. Thus, while we cannot categorically exclude the possibility that the sun affects climate (and hence marine sedimentation), the evidence available from thickness variation in varved sediments off Santa Barbara in southern California, for the last 500 years, is not demonstrably there.

Of course, just because we don't find convincing evidence in thickness variations of varves in one of the Santa Barbara cores does not mean that the proposed phenomenon does not exist. It just means that we cannot support the proposition of solar variation from these data, which are barren regarding the 11.1-year sunspot cycle and unconvincing with respect to the 205-year Suess cycle. Interestingly, analysis of a foraminiferal record in the Cariaco Basin published by D.E. Black of Stony Brook and associates yielded even less evidence for a solar effect (a Suess cycle was definitely not seen in their 825-year record). Thus, proven solar cycles do not show without fail in sediments.

Does the climate in fact vary with solar activity? Judging from ice-age information, it would seem that it can do so within a millennial time scale. The well-documented sun-forced Milankovitch fluctuations in deep-sea sediments, in polar ice, and in loess deposits involve tens of millennia, though. Perhaps what marine geology can contribute is to find locations where shorter periods are seen to have left a record also.

15.6.4 Bermuda Coral

Coral growth also may have information on variations in the environment. Presumably the building of a carbonate skeleton captures such information. However, the reaction of coral to solar variation, such as that of the massive *Montastraea cavernosa* studied by J. Pätzold and G. Wefer (then Kiel, now Bremen) in Bermuda, apparently is extremely complicated. One indeed finds cycles in the growth data, but they are not clearly linked to known solar forcing. The reason presumably has to do with the fact that supply of warm water and of nutrients are two fundamentally different growth requirements of the coral, implying at least two controlling factors (e.g., solar and tidal) that may interact. Interacting cycles of forcing may result in cyclic variations that are difficult to interpret.

15.7   Discussing the Future of Doing Marine Geology

Marine geologists (as is true for other scientists) are faced with the problem that we humans are on a path toward environmental catastrophe, according to a host of experts. (At least one well-known climatologist suggested in a popular book that we may generate a lifeless planet.) The chief concern is that we are ignoring unintended consequences of releasing carbon dioxide into the air. The greenhouse effect is a fact – it makes the planet habitable. Without the atmosphere and its greenhouse effects, our climate might be more like that of the moon, instead of what we have. There is no discussion or doubt about the benefit of greenhouse gas in the atmosphere. What is a matter of discussion among the experts is how much greenhouse gas is too much. As we

humans increase the relevant gas content in the atmosphere at a rate and to a level unprecedented in the last several thousand millennia, we do get serious warnings from well-respected scientists about undesirable consequences of doing so. The most frightening warning is about the prospect of a runaway effect from a massive release of the gas methane, fast enough to escape prompt microbial conversion to carbon dioxide and harmless water, by oxidation.

The most reliable of the awful projections is that sea-level rise will continue to accompany global warming. We can be 100% sure of that because sea-level rise is already happening and can now be measured quite reliably using satellites, videos, and listening devices. On the one hand, we have admonitions from a great number of working scientists that we cannot continue with business as usual without facing unacceptable risks. On the other hand, we have stern warnings from certain sociologists and politically active persons (including representatives of industry) about troublesome economic and political consequences from abandoning or greatly reducing carbon-based energy use. There also is a third message. The message from many Dutch engineers is this: let's make the dams higher, just in case. The arguments for all three messages have changed very little for decades. What *has* changed is a sense of urgency, a perception that we are running out of time for discussions.

Incidentally, serious skepticism is not the issue when examining the work of scientists, including that of marine geologists. All scientists are trained to be skeptical; that is, to prefer evidence over just-so assertions. When discussing the future development of climate, of course, there *is* no good evidence. The future, by definition, has not happened yet. Thus, there cannot be any records to study. Unfortunately, when our future does happen, it is likely to bring an unfamiliar world, a world even more poorly understood than the one we live in. Increasingly, therefore, as we get closer to an unfamiliar world, our projections are likely to be out of sync with reality. The task for marine geologists is to gather real evidence and to ignore assertions based on personal preference or fear (attitudes sometimes confused with "skepticism"). The task is, obviously, to help generate acceptable risks. Among the many challenges arising in the context, helping to avoid unintended consequences of purported remedial action is well worth tackling, as is the prospect of sea-level rise and methane runaway.

Suggestions for Further Reading

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