variability. Examples include the appearance and disappearance of tilefish off the east coast of the USA (Lorenzen, 1975) and the rise and decline of the West Greenland cod fishing (Cushing, 1976). The well-known El Nino phenomenon is another example of a climatic anomaly effect. Under such conditions coastal upwelling of nutrient-rich water is impeded and the Peruvian anchovy catch is reduced (Idyll, 1973; Cowles et al., 1977). A decrease of oceanic pH and a lowering of the super-saturation with respect to $CaCO_3$ caused by increase in dissolved CO_2 could influence the ability of marine organisms to form carbonate shells and skeletons (Elliott and Machta, 1978). In general, changes in atmospheric and oceanic circulation could affect marine productivity by changing the rate of upwelling, thereby influencing the fertility of surface waters.

It is often argued that some areas might benefit from an overall warming while others might suffer, insinuating that, on balance, there would be no adverse effects. Moreover, based on new developments in genetics and crop production methods some optimism has been expressed about the capability of some crops to adapt to slow changes in climate. There may be some justification for this regarding the industrialized nations with their highly developed organizational and technical skills, and the availability of capital and the necessary expertise. However, experience of the last decades has rather given rise to pessimism particularly in those developing countries that extend into areas with marginal climates. The increasing population pressure and the lack of capital and technological expertise make most developing nations, and hence the majority of the world's population, extremely vulnerable to even a slight variation in climate. Furthermore, there might be enormous costs for additional fertilizers, if, for example, the potential warming resulted in a shift of part of the USA corn and wheat belts into adjacent poorer soils. This would also necessitate a costly relocation of a complete infrastructure.

Finally, all of these factors may strain the finances of even the richest countries such that there may be little left to contribute to an aid program for the developing world. It would thus appear that any climatic change in any part of the world has to be viewed with great concern because the nations have become increasingly dependent upon each other.

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Measures of CO_2 control

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In the pessimistic, and tendentially masochistic, attitude that now seems to pervade western countries, measures of CO_2 control will be prima facie understood as rules and constraints that have to be imposed in order to reduce the consumption of fossil fuels.We may interpret the proposition of Prof. W.D. Nordhaus, to put a tax on CO_2 emissions, in this sense. This tax would be adjusted to keep the emission level under a predetermined value, that could be constant or a function of time (Nordhaus, 1977).

Such a proposal has much to recommend it. On the one hand, it respects the freedom of choice of the consumer, even if substantially restricting it, by operating in the conceptual framework of a market economy. On the other hand, it would find the enthusiastic support of bureaucrats and tax collectors, because it would add a new line to their activities. Properly injected with massive doses of guilty feeling, the consumer would presumably finally pay. Such a sequence has already been thoroughly tested in Europe, with the manipulation of gasoline prices.

The core of Nordhaus' reasoning is that the problem of CO_2 emission controls can be dealt with by a normal economic model where CO_2 *emission* is considered as a *resource* in short supply to be allocated between the various sectors of the economy in such a way as to maximize national income under this additional constraint.

The second line of thinking I strongly prefer as a matter of personal attitude, is that of the positive response: what can we do to avoid the worst?

Here 3 observations may help, in order to start thinking about a physically possible solution.

- Firstly, plants circulate in their system about 10% of the CO_2 in the atmosphere every year. The amount of CO_2 rejected by man is only a fraction of a percent. This fits with the parallel observation that plants have a metabolism in the range of 100 TW and man consumes less than 10 TW in the form of fossil fuel. So plants could give a hand, so to speak, to solve another of our problems.
- The 2nd observation is that the CO_2 ejected into the

atmosphere stays there for a while because of poor kinetics, not because of poor sinks. Deep ocean waters and the clays on the ocean floor have the capacity of digesting all the CO_2 we may reject during the next century, once it has been transported there. Oceans, however, are stratified and basically stable and the surface waters, equilibrated with the atmosphere, are brought down only in a few places and by a relatively limited amount.

- The 3rd observation is that the various kinds of geologic traps that were able to keep oil and gas in store for millions of years, would probably be able to store CO_2 as well, during the same geologic time scale.

These 3 observations give physical support to the basic concept of the fuel cycle in the same way as the data obtained from nuclear technology under qualitatively analogous pressures.

The modification of the standing crop and humus has been proposed by Dyson (1977), who suggests planting trees in fallow land. However, the proposal has 2 weak points, the 1st being a question of scale. The number of trees to be planted is in fact astronomical, and every person on earth should plant a couple of trees per week in order to break even with emissions somewhere after the turn of the century. But new ways of planting trees can be devised which bypass this bottleneck.

The 2nd weak point is that reforesting changes the local albedo and consequently the amount of energy absorbed from the incoming solar light (Otterman, 1977). We may finally be moving in the very direction of warming the earth that we are trying to avoid. Incidentally, this points to the fact that the earth's albedo is a sensitive factor in the earth's energy balance, and we could give a hand by painting our houses and streets white in order to reduce the warming up.

For the second sink, the ocean, there are 2 proposals. One by Revelle and Shapero (1978) suggests throwing phosphorus into the ocean superficial waters. As sea plant growth is basically phosphorus limited, this would increase plant productivity and the amount of litter falling into the deep ocean and transporting there the unwanted C, in the form of organic compounds. Algae have a total metabolism not much different from that of land plants, and so the orders of magnitudes are correct. Monocellular algae have a carbon-to-phosphorus ratio of about 100, so that taking the proposal at face value, the amount of phosphorus to be injected into the sea should be in the range of perhaps 100 MT/year. Not small, but feasible. One could use the Black Sea, already heavily eutrophicated, as a test bed.

In a similar vein, I proposed using thermohaline currents in their sinking mode to operate the deep injection (Marchetti, 1977, 1979). 2 huge currents are present in the Weddell Sea, in the Antarctic, sinking perhaps 20 MT of water per sec, and in the Norwegian Sea sinking perhaps 5. They are not very accessible sites, so I chose the Gibraltar current, sinking about 1 MT/sec of dense Mediterranean water into the Atlantic. This "megamixer" seems to work (Hoffert et al., 1979), but the real point is to collect the CO_2 for the injection. Environmental control has made us familiar with stack scrubbers to take away SO_2. The same scrubbers can be adapted to take away CO_2 also. The consumer may see his energy bill increase by perhaps 20% (Mustacchi et al., 1978), but he has already been trained to absorb that. Small fixed consumers may have to switch to low C fuels like methane, but they are doing it already, and vehicles may be left free with the option of using hydrogen whenever possible. These measures, which could be completed in a period of 30–40 years, could progressively bring emission to a constant level and then cause a decrease. There is no power system in sight, however, that would be able to introduce such measures, which after all are costly and benefit invisible people. As previously suggested, one should then try to find a positive solution through marketing mechanisms (Marchetti, 1979).

One ordinarily has the scrubber after the combustion chamber, as a device for separating CO_2 and SO_2 for disposal somewhere. One could also view it as a machine for separating N_2 for disposal in the atmosphere. In other words one could substitute it with an air separator in front of the combustion chamber. Using pure oxygen (at high pressure) as an oxidant has many advantages; power plants would become very small, silent, and they could claim zero emission. Perhaps this could pay off in certain cases, e.g. for power plants right in the centers of cities, and start a new line of development. Nitrogen and CO_2, at least in the beginning, could be sold for injecting into oil fields to improve recovery.

Incidentally, without going to the trouble of reinjecting CO_2 into the ocean, one can use observation number 3, and inject it into the appropriate geologic structures, of the type that held oil and gas for millions of years, which are very common, and are usually filled up with water.

I would like to terminate here this brief analysis of the problem of CO_2 management. I hope the objective has been reached of showing that the problem is highly articulated and can be brought to human dimensions. As thinking, assessing and maturing such technical concepts have quite long induction times and to begin with are relatively cheap, it may be a good tactic to foster such studies in parallel with the let's know better trend which is now dominant.