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TRANSFER PROCESSES AND TIME SCALES IN BIOGEOCHEMICAL CYCLES[☆]

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INTRODUCTION

Man's activities on earth have reached a pitch where he is becoming a factor of importance in global biogeochemical cycles. In order to understand the way in which we – intentionally or unintentionally – are changing our environment on a global scale, we need a much more thorough knowledge of the natural biogeochemical cycles forming the basis for the existence of the biosphere as we know it today. The carbon cycle is of prime concern in this context. The presence of oxygen in the atmosphere and its circulation are obviously of equal fundamental importance. The cycles of the minor constituents of the atmosphere and the oceans have become the subject of our attention only recently and it is becoming more and more obvious that they are of fundamental importance of our understanding of the way in which man is changing the environment. This is the basic reason why SCOPE initiated a series of surveys of some of the most important cycles of this kind. The cycles of three such constituents – namely, nitrogen, phosphorus and sulphur – are dealt with in this volume.

CHARACTERISTIC TIME SCALES

In attempting to describe the processes on earth that maintain the circulation of air, of water and of those constituents that are of importance for the existence of the biosphere, we must realise the necessity for distinguishing between processes geared to very different time scales. Life in the surface layers of the world's oceans interconnects several such cycles with a rather short characteristic time scale. Light, carbon dioxide and nutrients (primarily nitrogen compounds and phosphates) in the water are necessary for phytoplankton to grow. The latter provide the food of the zooplankton

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which in their turn form the chief food supply of fish. Most of the plankton dies naturally within days or weeks. Bacteria attack the dead matter, decomposing the organic compounds into organic compounds, which again become part of this same cycle. The characteristic time scale for this cycle is of the order of weeks or months.

The carbon dioxide flux from the atmosphere to the sea has a characteristic time scale of about five years. On the average, oxygen stays in the atmosphere for 10,000 years before it takes part in biological processes in plants or animals on land. The nitrogen molecule has to wait for some millions of years before passing into solution in seawater.

In studying global ecology, it is essential to have a clear perception of the time scale applying to the problem under study. Joint treatment of slow and fast processes in any particular cycle is generally not feasible. Processes that are very slow must be described by assuming that a steady state prevails. Quick processes, on the other hand, are generally described by some kind of dynamic equilibrium. The biological activity in the surface layers of the sea, for example, maintains processes of the latter type by which carbon, oxygen, nitrogen and phosphorus are assimilated by the biota in a certain ratio – C:O:N:P = = 106:138:16:1. Thus the cycles of these four elements are linked by the biological activity in the surface layers of the ocean.

The characteristic times for the different cycles are determined partly by the rate of mixing and transport of these compounds by the movements of the air and the water, and partly by the rates of the chemical and biological processes. Since the former rates are mostly the same for all compounds, it is appropriate first to try to obtain a picture of how the atmosphere is being mixed and likewise to determine the characteristic rates for the hydrological cycle, including the mixing of the ocean and the interplay between glaciers, sea ice and seawater. We shall return to this problem below.

COMPLEXITY VERSUS SIMPLICITY

A difficult problem, when we wish to model the global cycles, is the great complexity of the natural global system, primarily because of its inhomogeneity. For example, if we wish to describe the interaction between plants on land and carbon dioxide in the atmosphere, we must in some way quantitatively describe the assimilation of carbon dioxide. We may then also need take into account the fact that forests in temperate latitudes, cultivated fields, sparse vegetation in semiarid regions and dense vegetation in tropical rain forests exhibit great variations in this respect. In one case assimilation may perhaps be limited by low temperatures during part of the year, in another case by insufficient precipitation. In other cases there may be lack of nutrients in the soil or too little sunshine because of cloudiness. Only in a few cases has it been possible so far to make suitable allowance for such regional differences when studying global cycles. Thus, we must often be content with obtaining qualitative results or determining the order of magnitude of the fluxes that we wish to study. As one of the following articles will show, it may now be possible to study the sulphur cycle in greater detail.

This problem of inhomogeneities will always be with us. Even if we divide the earth into regions and permit interaction between them in our models, each of them will still feature inhomogeneities that we may have to disregard. The description in a simplified manner of what takes place in each part of a model of the biosphere, so that the overall interaction between different parts can be studied, is often called parameterization. This concept is well known from ecosystem analysis as well as from attempts at building climate models. Implicit examples of such parameterization will be found in several of the following articles.

TRANSFER DUE TO AIR MOVEMENT

As mentioned above, the movements of the atmosphere and of the water in the soil and in the oceans affect the distribution and flux of the various trace constituents in the same way. It is therefore of value to have an overall view of the characteristic time scales involved in the movements of air and water in nature.

Within the troposphere (the atmosphere below 8 to 16 km) the temperature decreases rather rapidly with altitude, which means that this part of the atmosphere is not infrequently unstable and that relatively quick vertical mixing of the air takes place. The characteristic vertical mixing time of the troposphere is little more than a month. The horizontal mixing within the troposphere is fairly effective outside the subtropical and tropical regions, where the winds are comparatively weak. The cyclones that form and move at middle and high latitudes and the westerly jet streams at an altitude of 10–12 km imply that within the polar regions down to the latitude of about 30°, the characteristic horizontal mixing time is a few months. The exchange of air between the northern and southern hemispheres is slower and we may accept a characteristic exchange time of 9–12 months. To a certain degree, one may look upon the tropical belt as a barrier for air exchange between the two hemispheres.

Conditions in the stratosphere are very different. This is due to the stable stratification caused by the absorption of solar ultraviolet radiation by ozone at levels between 30 and 60 km. The vertical exchange in the stratosphere is 50 to 100 times less effective than in the troposphere and the characteristic vertical exchange time is 5–10 years. Within the winter hemisphere, the horizontal mixing is as effective in the stratosphere as in the troposphere, that is, from the pole down to about latitude 30°. When the summer comes, the winds become steady and almost due easterly. In this way, the air is carried around the earth, but the north-south exchange is very limited.

TRANSFER DUE TO THE WATER CYCLE

The atmosphere contains on the averige 0.3 % water vapour by mass which corresponds to $1.5 \cdot 10^7$ Tg of water. The average precipitation on the earth may be given as about one metre per year, which is equivalent to $5 \cdot 10^8$ Tg. This means that a water vapour molecule spends, on an average, about ten days in the atmosphere before it is brought back to the earth's surface in the form of rain or snow. The possibility of direct exchange of water molecules between the atmosphere and sea makes it more likely, however, that a water molecule leaving the sea surface is returned to the sea by direct gas exchange rather than by precipitation. The residence time of a water molecule in the atmosphere is thus, in reality, considerably shorter than given above.

Even if the mean residence time from evaporation at the sea surface to precipitation is about 10 days, the average time between two successive occasions on which an air mass takes part in cloud formation is shorter, since part of the water vapour in a cloud is never converted into rain or snow. Gases that dissolve in water (for example sulphur dioxide or carbon dioxide) or dust and particles incorporated into clouds and raindrops, have a residence time in the atmosphere differing from that of water vapour, depending upon the solubility of the gas or the rate with which the particles are incorporated into clouds and rain. Readily soluble gases penetrate to levels above a few kilometres only to a very limited extent since the time between two successive rainfalls from the same air mass is rather short compared with the vertical mixing time of the troposphere, which is more than a month. Their residence time in the atmosphere may be a few days to a week or two depending upon the frequency of rains. These circumstances thus effectively limit the amount of sulphur dioxide reaching the tropopause to only some few per mille of the amount brought into the atmosphere near the earth's surface. On the other hand, the mixing of carbon dioxide in the atmosphere is practically uninfluenced by the presence of water vapour, because of its low solubility in clouds and rain drops.

Evaporation and precipitation are not equally distributed over the globe. In the tropics, intense evaporation occurs, the air ascends and the precipitation therefore has a maximum in the vicinity of the equator, the intertropical convergence zone. At subtropical latitudes, the air circulation effectively prevents the release of precipitation and at these latitudes evaporation by far exceeds precipitation. Closer to the poles evaporation decreases, precipitation again being in excess. These circumstances imply a steady net flow of water vapour from equatorial regions towards the two poles. Across the 40° parallels this flux is about 2 Tg s^{-1}, that is, about as much as the flux of 20 rivers of the magnitude of the Amazon river. In a corresponding manner the winds each second carry a few million tons of water in over the continents. However, only about one-third of the total rainfall reaches the rivers and is thus transported back to the sea. The remainder evaporates, and is again brought out over the oceans by the winds.

The residence time for water on land (as snow and ice) or in lakes and rivers or in the soil (as soil water and groundwater) varies from a few weeks to many years. The snow in the small Scandinavian glaciers is a few hundred years old and the deepest parts of the Greenland ice pack are more than ten thousand years old. The ice in Antarctica is very much older. Shallow and small lakes do not retain the water for many weeks or months. The residence time for the water in deep lakes with small catchment areas may be years or decades. The deep groundwater reservoirs also often contain old water. These conditions are obviously of importance when discussing the water circulation and the resultant flux of other components being carried by the water.

TRANSFER DUE TO OCEAN CIRCULATION

The oceans cover about 70 % of the earth's surface and contain $1.3 \cdot 10^{12}$ Tg of water. The winds create a system of ocean currents that bring about a north-south exchange of water, a few years being required for completion of such a circulation. These currents effect a considerable transport of heat and also of chemical constituents. The differential heating between the poles and the equator establishes a characteristic stratification of the world oceans and also a thermally driven circulation. Between about 45°N and 45°S, the surface layers of the sea are comparatively warm while the temperature rapidly decreases below the thermocline at a depth of some hundred metres. In spite of the high salinity in subtropical regions caused by intensive evaporation, the surface waters are less dense than the water at greater depths, depending upon the high temperature. Winds and currents are unable to bring about any significant vertical mixing down to the thermocline. Only within rather small parts of the world oceans does the surface water become sufficiently cold and saline so as to sink to greater depths than about one thousand metres. This occurs in the winter when the ice forms and the salinity of the water thereby increases, primarily in some parts of the North Polar Sea, within a small region in the Greenland–Iceland area and in the Weddell Sea in the Antarctic.

The water that sinks in the North Atlantic finds its way southwards primarily along the North American coast and from there into the deep ocean basins. In the South Atlantic the cold North Atlantic water mixes somewhat with the Antarctic bottom water and then flows into the Pacific Ocean and the Indian Ocean. In this way a slow vertical circulation of the oceans is maintained but it takes several hundred years before the North Atlantic water reaches the South Seas and about a thousand years before it again comes in contact with the atmosphere at the surface of the Pacific or Indian Oceans.

This slow circulation of the sea implies that only the upper layers play a role for the rather rapid cycles of various constituents of the biosphere. These cycles are initiated by the motions of the atmosphere, the evaporation and condensation of water and its flux back to the sea as soil water, ground water and rivers and also by man's pertubation on these comparatively rapid processes. Many of these cycles are interlinked via ocean circulation. Man-made emissions mostly end up in the sea. Thus, possible changes in the chemistry and the biology of the oceans often turn out to be critical factors when global environmental problems are considered.

THE INTERPLAY OF VARIOUS CYCLES

In trying to model various cycles of important elements in the biosphere, we should make maximum use of the fact that the transfers of these constituents due to the motions of the air and the water in many regards are similar. The biogeochemical processes simultaneously involve several of the constituents with which we are concerned. As indicated earlier, the growth of phytoplankton in the sea, for example, implies rather well defined proportions of how such elements are incorporated into organic matter and therefore the cycle of these constituents are closely interlinked through the growth of biota in the sea. Similarly, the inorganic chemical processes also imply the release or injection of constituents into the air or water streams in rather precise ratios. Because of these circumstances, it is obviously most important to deal with the cycles of the main substances simultaneously. The cycles of carbon, oxygen, nitrogen, phosphorus and perhaps sulphur are especially interrelated – a fact which should be considered when dealing with global cycles. In their study of transfer of matter in the ocean, Keeling & Bolin

(1967; 1968) tried to study the interrelation of these elements in the sea, using a very simple model of the oceans and their circulation. Even though the quantitative results must be considered as very preliminary, it is interesting to note how the joint treatment of several of these cycles implies constraints which are most valuable for a proper understanding of the characteristics of these various cycles. Extended analysis based upon our more detailed knowledge of the dynamics of the atmosphere and particularly of the oceans (Veronis, 1975) may be expected to yield valuable information about the role of the movements of air and water in biogeochemical cycles.

This is not the place for a detailed discussion of the interplay between various biogeochemical cycles, but it should be emphasized that it is important to treat them jointly. Further progress in this field will largely depend upon our capability to interrelate them in the way briefly sketched above.

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