or scattering at one wavelength will provide data about relative concentrations of particles within the water column, spectral data from these sensors combined with absorption measurements can move us a long way toward characterizing the aggregation into various biological and inorganic components.

Summary

Transmissometry and nephelometry provide increasingly valuable information relating to the light-transmitting characteristics of water as well as an idea of the relative concentration of suspended material within lakes and oceans. While sometimes viewed as near-synonymous techniques, these methods use different measurement methods, provide different products, and have different strengths and weaknesses in considering the applications to which they are applied. Applications vary widely and across numerous disciplines, but tend to be divided into two major classes: those that attempt to characterize the fundamental optical properties of the water; and those that seek the relative concentrations of foreign particulate matter in the water. In general, nephelometry is the preferred technique in environmental and fresh water applications and transmissometry is more common in oceanographic research. Although transmissometry and nephelometry differ as measurement techniques, in their application domains, and in subsequent calibration and handling, all of these sensors are capable of providing outputs in terms of absolute coefficients that describe the fate of light passing through water. These coefficients of light transfer are collectively known as the inherent optical properties or IOPs. Their values are related through the volume scattering function that describes scattering as a function of angle into which light is deflected. While these sensors play an increasing role in observing in water processes, they also provide a technological foundation for a new generation of sensors that extend IOP capabilities. These new sensors hold the ability to determine absorption coefficients, to determine coefficients as a function of wavelength, and to characterize the volume scattering function at more than one angle. These improvements not only allow more complete characterization of natural waters but also provide a tangible means of relating remotely sensed data from air and space to in-water processes.

See also

Optical Particle Characterization. Radiative Transfer in the Ocean. Satellite Remote Sensing Microwave Scatterometers. Turbulence Sensors.

Further Reading

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TRAPPED PARTICULATE FLUX

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The transportation of biogenic and lithogenic particles from the upper ocean to the deeper ocean layers and to the ocean floor by vertical settling is one of the key processes to understand the biogeochemical cycles in the ocean. The rate of the export of particles from the euphotic layer to the oceanic interior, oceanic particle flux, is the product of the settling speed and the mass of particles. A particle whose specific gravity is equal to or lighter than sea water cannot be a part of the vertical flux; these particles are called 'suspended particles' in contrast to 'settling particles.' All ocean particles settling through an ocean water column have a role in removing atmospheric CO_2 to its deep oceanic sink.

Atmospheric CO_2 is photosynthesized to form particulate organic carbon as phytoplankton cell material in the euphotic layer. The majority of organic carbon particles that result from primary production are metabolized and remineralized to CO_2 as they settle through the oceanic water column. Remineralized CO_2 is recycled to the atmosphere. The residence time of remineralized CO_2 depends on the depth; it can be in an instant at the surface film to the order of decades in the mesopelagic layers. A portion of the particulate organic carbon that escaped from the remineralization process is successfully exported to the deeper ocean interior layers or to the ocean floor. These organic carbon particles are also, eventually, recycled to CO_2 but a far slower rate of ventilation keeps dissolved CO_2 in oceanic interior for the millennium timescale. This process of removing atmospheric CO_2 to the interior sink of the ocean by means of settling organic carbon is called a 'biological pump.'

Removal of calcium carbonate particles by specific plankton decreases surface water alkalinity, thereby counteracting the effect of the biological pump by making the oceanic surface less absorbent to atmospheric CO_2. However, the partial dissolution of calcium carbonate in the water column and the sediment at deep sea surface regenerates alkalinity in deep water. This export of CO_2 and alkalinity from the surface to deep water is then balanced by their resupply from the deep to surface water as a result of global thermohaline circulation. The effectiveness in removing CO_2 from the atmosphere to the deep sea thus depends on the rate of export of organic carbon particles, the ratio of organic carbon to inorganic carbon (the so-called 'rain ratio') in the settling particles, and the residence time of the metabolic, dissolved CO_2 and the rate of the regeneration of alkalinity in the deep-sea; the latter depends on the depth of regeneration and the turnover time of deep and intermediate waters.

The spatial and temporal variability of the oceanic particle flux can be measured by capturing settling particles with 'sediment traps.' A sediment trap comprises a horizontal open area ('aperture') and a shutter mechanism to expose the aperture for a specific time period. A sediment trap is not only used to estimate the quantity and rate of particle export, but also to investigate the collected particles by various laboratory methods including chemical analysis and microscopy. Modern sediment traps have time-fractionating, sequential samplers so that export rates can be measured in a continuous time-series. Particles are exported from the ocean surface to the bottom sediment with the imprint of the habitat in which they were produced. This memory is useful to compare the past environment of the ocean and atmosphere with the fossil counterpart. Therefore, semifossils collected in sediment traps often called 'ocean biocoenosis,' serve as a useful proxy to understand the past.

Time-series sediment trap data have revealed that operation of the biological pump is strongly seasonal. Particularly in the moderate and high latitudinal ocean areas, the majority of annual export of organic carbon in the oceanic interior is accomplished in a relatively short time during a bloom. In general, export is firmly tied to surface productivity at any depth. As an example, when a cold eddy with high productivity passes over a sediment trap mooring, a pulse of organic carbon particle export is observed at that sediment trap depth in the ocean interior. In contrast, only a traceable particle flux is observed when the euphotic layer is exhausted of nutrients immediately after the spring bloom or under an extensive sea-ice cover.

The majority of settling particles are so-called 'marine snow' and fecal pellets produced by a micro- and mesozooplankton. Other particles are independently sinking shells and skeletons of planktonic organism such as the shells of foraminifera and pteropods. A marine snow particle is an aggregate of detritus that is agglutinated to an amorphous substrate or 'matrix.' Fibrous matter such as an abandoned larvacean houses, degraded gelatinous material and microbial by-products often comprise the matrix. The amorphous particles are highly variable in size in the upper ocean layers, ranging from less than a millimeter to as large as 10 cm and often appear as a piece of string that hangs in water. Amorphous aggregates become more uniform and smaller, about 0.5 mm in diameter, while settling through the deeper layers. Small fecal pellets are often stuck to the matrix, and they settle together. The majority of fecal pellets that arrive at the ocean interior are products of microzooplankton such as calanoid copepods of a few hundred micrometers to a half millimeter long. While in the water column, particularly in the upper layers, amorphous aggregates are always in transit, being broken into pieces, re-merging into other settling particles, which are often grazed and transferred to the fecal pellet phase. This process, switching from suspended particles to aggregates phase and vice versa, is repeated many times while materials are net-transported downward.

A flake of marine snow or a fecal pellet is a microcosmos that represents the biological complexity of the upper ocean. The composition of exported particles is altered from the originally produced particles in the upper ocean. The constituents of settling particles can be categorized into four principal components: organic matter, $CaCO_3$, biogenic opal (amorphous SiO_2), and lithogenic particles that originated from the airborne particles that fall from the ocean surface. These four components work together to: (1) remove organic particles from the euphotic layer and transport them to the oceanic interior sea floor sink by the biological pump; (2) supply food to the benthic community; (3) supply carbonate particles to the seafloor that add alkalinity to the deep and bottom water; and (4) form a sedimentary sequence by depositing refractory particles that survived from the chemical and biological processing at the bottom.

In order to keep exporting atmospheric CO_2 to the oceanic interior, organic carbon particles must be removed consistently from the upper layers. However, most organic carbon particles that are produced in the euphotic layer are about equal in specific gravity to sea water or even lighter than sea water. Therefore, an aggregate and fecal pellets must be ballasted by material with higher specific gravity. Coccoliths are ideal ballast because they are ubiquitously available in the euphotic layer and the $CaCO_3$ crystals that compose a coccolith are the heaviest common material in the open ocean. Lithogenic particles also serve as ballast. The vertical settling speed of all oceanic particles, including particulate organic carbon, that are hosted by settling particles is estimated, as a result of time-series sediment trap experiments, as 100–200 m per day; it takes an average marine settling particle several weeks to arrive in the interior sink from the time they were produced in the surface layers.

Organic compounds in settling particles are a mixture of the deliberative materials that are produced by photosynthesis and compounds that are generated by microbial products. Microscopically, original phytoplankton cells are rarely preserved in settling particles or in fecal pellets. It is reported that over 70% of the organic compounds in settling particles are unidentifiable because they are altered from the original material produced in the upper layers. Fluxes of organic matter decrease in three numerical modes. (1) There is an exponential decrease in the upper ocean layers due to the active metabolism leaving only about 10% of primary production at the bottom of the euphotic layer. (2) Metabolism of particulate organic carbon continues in the mesopelagic layer, down to about 1 km deep and the flux of organic carbon decreases in a rapid linear mode. (3) Organic carbon particle flux decreases in the bathypelagic layers far more slowly than in the shallower layers.

$CaCO_3$ particles provide the inorganic carbon export to the ocean's interior; they consist of three major classes reflecting the production in the upper layers: (1) coccoliths, calcite exoskeletons of single-cell phytoplankton called coccolithophores, a few to 10 μm, that settle with aggregates playing the role as a ballast; (2) calcite shells of planktonic foraminifera, an ameba-like zooplankton of a few hundred micrometers, that settle by themselves; and (3) aragonitic shells produced by pteropod snails in the high latitude oceans. An adult pteropod shell ranges in the order of millimeters. Export of magnesium-rich calcite particles in the open ocean has not so far been reported except in the relatively rare case of lateral transportation from coral reefs. Although all these carbonate particles remove alkalinity while they are formed in the surface ocean, it has been hypothesized that the residence time of these particles is too short for them to dissolve, and therefore recycling of alkalinity would not take place in the water column but only at the deep ocean bottom based on microscopic evidence. Thereby the flux of $CaCO_3$ particles is close to the production rate. However, this hypothesis has been challenged.

Most of the representative ocean basins including the Arctic and Antarctic Oceans have been covered by year-round sediment trap stations since 1983; as yet the particle flux data are still too scarce for them to be used as global figures of the carbon fluxes at the oceanic interior pool of CO_2. A recent estimate of global export flux of organic carbon to the ocean's interior, based on sediment trap measurements, is 0.35 Gt (10^9 tonnes). Or, the average organic carbon flux in a year per square meter of world ocean is 960 mg. Similarly, it is estimated that 0.39 Gt $year^{-1}$ of inorganic carbon associated with $CaCO_3$ is exported to the interior of the global ocean, that is 1200 mg of flux m^{-2} $year^{-1}$. The global ratio (in mole) between organic and inorganic carbon flux at the sink, the 'rain ratio,' is about 0.8. When a recent estimate of global oceanic primary production, 40 Gt $year^{-1}$, is applied, about 0.9% of primary production is exported to the ocean interior sink.

Silicon molecules are exported from the surface layers to the interior of ocean with settling particles as biogenic opal and lithogenic silica. Oceanic biogenic SiO_2 mostly consists of poorly crystallized polymorphs of silica – biogenic opal. Radiolarian tests are a zooplankton counterpart. Globally, the majority of biogenic opal particle export is attained by diatom frustules. Silicoflagellate skeletons often constitute a few percent of the total biogenic opal flux in a low-latitude ocean. In general, about 40–70% of the opal–SiO_2 particles are dissolved before reaching the interior sink. An estimate of global flux of silicon in the ocean interior is 0.72 Gt year^{-1}. The global Ca (in carbonate particles) and Si (in biogenic opal particles) export fluxes at the oceanic interior are 2.9 and 1.4 Gt year^{-1}, respectively.

The density of lithogenic particles, clay and fragments of rock-forming mineral particles, that are brown from dry land, suspended in the air above the oceans differs by several orders of magnitude by locations, depending on global atmospheric advection patterns and distance from the source. Unlike biogenic ocean particles, airborne particles that arrive at the deep seafloor are hardly altered from the time they fall onto the ocean surface, and can therefore be considered a proxy for atmospheric circulation. Lithogenic particles may play critical roles in supplying micronutrients, particularly dissolved iron. Lithogenic particles ballast aggregates to settle and remove organic carbon particles from the upper ocean as coccoliths do.

Current export flux data reveals distinct 'biogeochemical regions' where the biological pump operates in two significantly different modes. In one the export of $CaCO_3$ particles is dominant over opal particles. In the other the export of opal particles is dominant over $CaCO_3$ particles; the mole ratio of Si in biogenic opal particles to the inorganic carbon from $CaCO_3$ particles (Si/C ratio) is higher than 1. The opal export-dominated domain occupies the cold water regions except the polar oceans and covers less than 20% of the present global ocean. The subarctic Pacific – including the area north of 45°N, the Bering Sea, the Sea of Okhotsk and the northern East Sea (Japan Sea) – and the Southern Ocean to the south of the Subantarctic Polar front are opal export-dominated oceans. This difference is caused by the availability of dissolved SiO_2 in the water column, and the mixing and upwelling of the thermohaline circulation. The moderate and tropical basins of the Pacific and Indian Ocean are carbonate-export dominated (the Si/C ratio is smaller than 1) ocean. Most of the North and South Atlantic Ocean including the Nordic Seas are $CaCO_3$-dominated oceans except for the Atlantic Southern Ocean.

In the Pacific Ocean the Subarctic and Subantarctic Front demarcate these two biogeochemical regions; the poleward areas of the fronts are opal-export dominated. Opal export-dominated ocean removes atmospheric CO_2 more efficiently because it is usually associated with higher export of organic carbon with a higher rain ratio. The processes of sequestering opal do not affect the alkalinity. On the other hand, carbonate particles that are exported to the deep ocean floor generate alkalinity by dissolution and contribute alkalinity when deep water is recycled to the surface ocean by global thermohaline circulation in a millennium order of timescale.

See also

Calcium Carbonates. Carbon Cycle. Carbon Dioxide (CO_2) Cycle. Marine Silica Cycle. Marine Snow.

TRITIUM–HELIUM DATING

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Introduction: Tritium in the Oceans

Tritium (^3H) is the heaviest isotope of hydrogen. Its nucleus consists of one proton (making it hydrogen) and two neutrons. Inasmuch as it is chemically hydrogen, tritium exists within the global environment primarily as part of the water molecule. Thus it is a potentially useful tracer of the hydrologic cycle, and an ideal tracer of water motions within the ocean. Tritium is radioactive, decaying with a half-life of 12.45 years to the stable, inert daughter isotope ^3He. Because of its geologically short half-life, there is very little natural tritium in the environment. Small quantities are created by cosmic ray spallation (i.e. the smashing of atomic nuclei into small fragments by high-energy