19 Particle Flux in the Ocean: Summary

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19.1 INTRODUCTION

The production of particles in the upper ocean and their removal to the deep sea determine the distribution of biogeochemical elements in seawater, fuel benthic life and is the source of sediments accumulating on the seafloor. The diagenetic alteration, decomposition and dissolution of particles during sinking control together with ocean circulation the distribution of oxygen, nutrients, CO_2 and many other trace constituents in seawater. Understanding the processes of particle formation in the upper ocean and of their transport and transformation throughout the water column is therefore crucial in determining the role of the oceans in global cycles of carbon and other associated elements.

The preceding chapters have addressed a wide range of issues related to the study of particle flux in the ocean including: (i) methods of marine particle flux studies, (ii) sources of marine particles and their variability, (iii) case studies of particle flux measurements using time-series sediment traps in different marine environments and (iv) the potential of long-term particle flux measurements to monitor global environmental and climatic changes. The focus is on settling particles in the ocean, their source, their mode of formation in the upper ocean and their transformation within the water column during sinking.

Direct measurements of fluxes of settling particles from the surface ocean to the deep sea and their spatial and temporal variability have become possible only with the advent of time-series sediment traps (Honjo, Chapter 7). Prior to this, studies on particles in the ocean were based on samples collected by conventional water samplers. This technique allowed the collection of suspended particles. Larger particles which constitute the bulk of particles settling to the seabottom often escaped sampling by these techniques. Sediment traps are specially designed instruments which can be moored at various depths in the sea and which allow the collection of settling particles at intervals of hours to years. Honjo (Chapter 7) gives an overview of the definitions, the units and the methods involved in the measurement of particle flux in the ocean and provides a global comparison of particle flux data based on information collected from a wide variety of environments during the last two decades.

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19.2 PARTICLE SOURCES

The prime source of particles in the ocean is marine biological production. Particles are also introduced into the sea from the atmosphere and by the rivers. Dust inputs have been rarely measured directly due to problems associated with the measurements of dry deposition (Prospero, Chapter 3). Estimates based on aerosol data show dust inputs to be highly variable in space and time with most of the input occurring within very few precipitation events, as brief and infrequent pulses. They are a source of nutrients and essential elements (such as iron) to marine plankton. The atmospheric source is subject to anthropogenic perturbations.

Rivers introduce dissolved and particulate nutrients which stimulate biological particle production especially in coastal waters (Depetris, Chapter 4). The bulk of river-transported material is trapped in deltas and estuaries. A small fraction escapes to the ocean, especially in areas where rivers are connected to the deep sea by canyons. Episodic events such as floods enhance the transfer of river-derived material to deep basins. Small mountain streams are important in this connection. River inputs into the oceans are affected by human activities in the drainage basins such as deforestation which increases erosion and sediment transport, and the construction of dams and barrages which reduces sediment transport due to retention in reservoirs.

19.3 METHODS AND PROBLEMS

Asper (Chapter 5) and Honjo (Chapter 7) discuss the methods of investigation of particle flux in the ocean and the associated problems. The identified problems include: (i) hydrodynamic bias in the collection efficiency of sediment traps caused by the flow of water relative to the trap opening, (ii) artificial enhancement of particle collection by zooplankton which actively enter the trap and die (referred to as "swimmers") and, (iii) remineralization or degradation of the particles during the interval of time between their arrival in the trap and retrieval of the sample.

The potential of large hydrodynamic biases makes the collection of environmental data (e.g., ocean currents) extremely important during particle flux monitoring. Measurements of natural radionuclides in sediment-trap samples can provide useful limits on the degree of hydrodynamic bias during trap deployments (Bacon, Chapter 6). The degree of bias will be determined by the degree of agreement between the measured and the expected fluxes. Also here, the knowledge of the effects of horizontal transport and temporal variability of the balance between supply and removal of the reactive daughter nuclides is a prerequisite for data interpretation. The tracer results can be used to correct flux data where hydrodynamic bias occurs. Evidence based on ^{230}Th and ^{231}Pa suggests that properly designed sediment traps moored in quiescent conditions in the deep ocean (away from boundary currents) can be considered accurate to within ± 25% or better whereas significant hydrodynamic biases may occur in traps deployed in the upper ocean. Further work is needed to delineate the conditions under which reliable results can be obtained.

The problem of swimmers is being dealt with in several ways. They include hand picking of the remains of the organisms out of the sample, the use of screens over trap mouth to prevent swimmers from entering the trap and the use of mechanical devices to exclude the swimmers.

The simplest way to prevent the decomposition of samples is the use of a preservative. The commonly used preservative is mercuric chloride, but others such as formalin and sodium azide have also been used depending on the type of the planned investigation. The analysis of the supernatant fluids associated with the sediment trap samples is useful to identify any decomposition that might have occurred and, to apply the necessary corrections to the measured particle fluxes.

The reliable interpretation of time-series data collected by sediment traps from the deep sea requires that simultaneous time-series information is available on atmospheric and upper ocean processes (Schlüssel, Chapter 2). This includes information on: (i) the flux of material from rivers, atmospheric dust inputs and marine biological production, and (ii) the physical parameters affecting the dynamics of the upper ocean such as wind, rainfall, sea surface temperature and the extent of sea ice. Observations from space provide extensive global collection of such information and represent probably the only source of synoptic information on large areas of the global atmosphere and ocean. The planned amendment and the replacement of the current operational satellites by orbiters carrying advanced and newly developed instruments will benefit research on particle flux in the ocean.

19.4 RESULTS FROM EXPERIMENTS

The results from the experiment in the Sargasso Sea were the first to show that the flux of material to the ocean's interior varies seasonally and in pulse with primary productivity in the surface layers (Deuser, Chapter 9). This seasonal pulse is discernible in each of the 16 years for which data are now available. An important aspect of the results are the observed periodicities of 2–6 months discerned from the data collected at biweekly sampling intervals.

In the temperate and subarctic North Atlantic more than half of the annual flux to the ocean's interior is related to plankton blooms in the surface layers (Honjo, Chapter 7). The propagation of the blooms from south to north was recorded in the delay in peak fluxes measured by traps moored at various locations.

The pattern of fluxes to the deep sea at two sites located close to each other in the eastern equatorial Atlantic (Fischer and Wefer, Chapter 10) was consistent with the high spatial and temporal variability of the study area with respect to surface water properties, the extent of the upwelling area and atmospheric circulation (e.g., Inter Tropical Convergence Zone movements).

Few changes have been found in total particle flux to the deep equatorial Pacific Ocean over a year. However, biogenic silica and C_{org} fluxes showed an upwelling-related variability (Honjo, Chapter 7). Further results from the Pacific come from the Philippine and Caroline Basins in the region of the North Equatorial Current (NEC) and the Equatorial Counter Current (ECC), respectively (Kempe and Knaack, Chapter 17). Observations at both sites recorded low fluxes consistent with the prevailing nutrient regime in the area. A slight variability in fluxes was observed which was related to changes in the direction of water mass movements.

In regions of the western and eastern North Pacific such as the Gulf of Alaska, Bering Sea and in the Sea of Okhotsk, particle flux patterns were characterized by a succession of events (Honjo, Chapter 7) with high fluxes of biogenic silica with diatom frustules in spring and culminating with a $CaCO_3$ flux peak in autumn.

The relationship between upper ocean processes induced by the Asian monsoon and the particle flux to the deep sea is described by Haake et al. (Chapter 14) based on a record from three locations across the Arabian Sea in the northern Indian Ocean. All locations exhibited a bimodal flux pattern with peaks during the SW and NE monsoons. The temporal variability of particle flux to the deep sea during the monsoons reflected the changes in the upper ocean plankton community structure brought about by changes in the nutrient regime: high $CaCO_3$ fluxes related to coccolithophorid blooms were followed by high biogenic silica fluxes from diatom blooms.

Schäfer et al. (Chapter 15) report on the pattern of particle flux in the Bay of Bengal, a marine region which comes under the influence of some of the largest rivers of the world with their high fresh water and sediment inputs. While the total flux is largely determined by the amount of lithogenic material, its nature is determined by the seasonal changes in the upper ocean plankton community structure. So for example, the biogenic fluxes are characterized by low carbonate/opal ratios and, as a result, high organic carbon/carbonate-carbon ratios (C_{org}/$C_{Carbonate}$) during periods of high fresh water discharge. At locations away from the influence of rivers, wind-driven biological processes determine the nature and quantity of fluxes. Such river-induced effects are common for even a low sediment discharge river such as the São Francisco River, which influenced the production and sedimentation of organic matter along the Brazilian coastal margin (Jennerjahn et al., Chapter 11).

In the South China Sea the particle flux pattern was closely related to the monsoonal wind-regime and the associated oceanographic processes (Wiesner et al., Chapter 16). Spectacularly high fluxes were recorded in this area from the introduction of volcanic dust (9012 g m^{-2}) from the 1991 eruption of the Mount Pinatubo (Philippines). The high fluxes were recorded simultaneously in mid and deep water within less than 3 days after the release of the major eruption plume. Furthermore, dissolved silicate released from volcanic ash affected the upper ocean plankton community structure in the following year, when biogenic silica was a major component of the flux of material to the deep sea.

Particle flux appears to be controlled not only by primary productivity in the surface ocean and the inputs from external sources but also by the primary producer-grazer relationship (Bathmann, Chapter 13). Evidence for this comes from the exceptionally low vertical flux, particularly in winter, in the central, seasonally ice covered Weddell Sea. This low flux is not related to a corresponding decrease in productivity but to intense grazing by an active population of zooplankton which thrive on the algae flushed from the ice during brine discharge. On the other hand, mass sedimentation resulting from blooms of phytoplankton was encountered in open ocean waters along the Polar Frontal zone in the absence of grazers (krill, calanoid copepods and salps).

Along continental margins, the general circulation of water masses, seasonal changes of continental inputs and marine productivity control the pattern of particle flux (Etcheber et al., Chapter 12). The results from the Atlantic and the Mediterranean show that particle fluxes decrease in an offshore direction. They increase with depth where particle injection into the ocean's interior from shelf and slope environments occurs. In the Mediterranean, fluxes are minimal in summer and maximal in winter. Seasonal variability is less pronounced along the Atlantic margin. An enrichment of C_{org} is also observed in these margins. The biogeochemical characteristics of this material are determined by inputs from marine and continental sources as well as by changes in the rates of decomposition.

Kempe and Schaumburg (Chapter 18) present data on particle flux within the largest and deepest fresh water body on earth, the Lake Baikal. The pattern of particle flux is bimodal with peaks in winter and summer. Resuspended sediments and biogenic material produced in the surface layer are the major particle sources.

19.5 ENVIRONMENTAL SIGNALS

Not all the material leaving the oceanic surface waters reaches the deep sea. Significant losses or decomposition have been found to occur in the biogenic components (Honjo, Chapter 7). The quantification of these losses, taking into account both the dissolved and particulate constituents, is just beginning to be attempted. In certain areas of the oceans such as the Atlantic only 30% silica, and about 1–3% organic matter, with regard to the initial amount leaving the surface reaches a water depth of 2000 m. Where increases have been found in the fluxes of lithogenic material with depth lateral transports are indicated.

Despite these losses or degradation, signals of processes in the surface layers of the sea can be recognized without much delay in settling particles sampled in the deep sea. This is recorded not just in the total and component fluxes but also in the detailed chemical nature, and planktonic and stable isotopic composition of the settling material. Of special interest is the stable carbon and nitrogen isotopic composition (Curry et al., 1992; Altabet, Chapter 8). For example, seasonal variations have been observed in the stable nitrogen isotopic composition of settling particles in various oceanic environments, which are related to the nutrient situation in the surface layers. In certain marine regions such as the Arabian Sea, signals of denitrification are recorded in the nitrogen isotopic composition (Schäfer and Ittekkot, 1993). These signals are also preserved in bottom sediments, where they have been used to infer past changes in marine denitrification processes (Altabet et al., 1995).

19.6 PARTICLE FLUX AND CARBON STORAGE IN THE DEEP SEA

The rapid transfer of material to the deep sea from the surface layers occurs because most of the flux is in large aggregates with high settling rates. They include fecal pellets ejected by filter-feeding zooplankton and particle aggregates held together by organic matter ("marine snow") released from plankton. Fecal pellets and marine snow have high sinking rates (400 to > 1000 m d^{-1}) and can transit a 3 km water column in about a week (e.g., Alldredge and Silver, 1988; Honjo, Chapter 7). Both are susceptible to bacterial attack and decomposition in the water column, which will depend on how long the aggregates remain suspended there. Fecal pellets and macroaggregates are found to contain both biogenic and significant amounts of lithogenic material, including riverine and aeolian particles. The incorporation of mineral particles such as clays into large aggregates increase their settling rates (Fowler and Knauer, 1986) and, as a consequence, effect the rapid transfer of both minerals and the freshly produced organic matter to the deep ocean (Ittekkot et al., 1992). This organic-mineral interaction is of relevance to the removal of atmospheric CO_2 and its storage in the deep sea (Figure 19.1).

Time-series sediment trap experiments with seasonal resolution have shown that the material arriving at the sea floor during periods of high fluxes is enriched in labile organic matter (Haake et al., Chapter 14). During high abiogenic fluxes in the Arabian Sea, the intermediate layers are characterized by seasonal changes in C_{org} as well as in labile organic constituents such as amino acids (their abundances as well as their spectral distributions), which indicate a reduced degradation (Haake et al., 1992). Consequently, the deep ocean receives relatively higher quantities of fresh, labile material, which has the potential to be degraded at the sediment-water interface.

Information on the degradation of organic matter in the deep sea may be obtained in part by comparing the fluxes of C_{org} measured in deep-moored traps with accumulation rates in the underlying sediments. The C_{org} content of settling

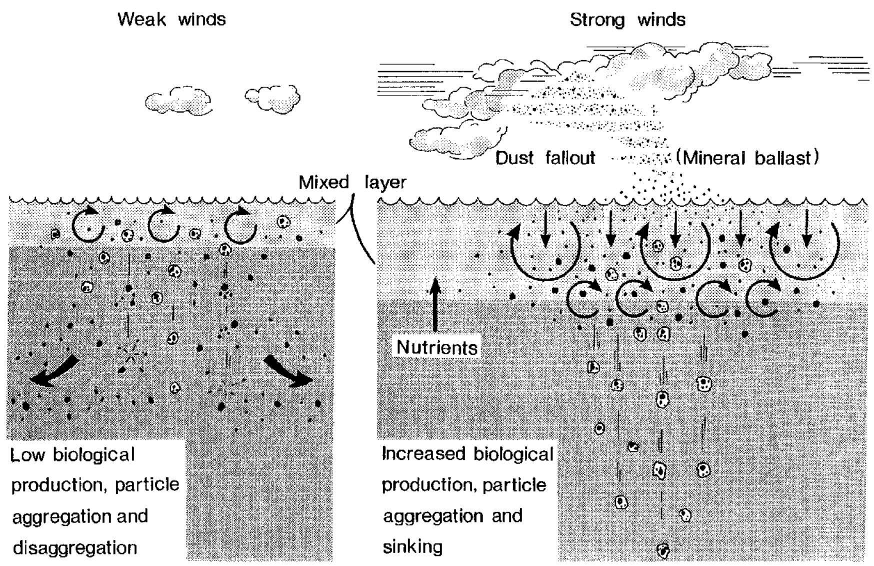

Figure 19.1 Schematic of processes that control organic matter production and removal to the deep sea. Dust particles deposited at the sea surface not only introduce essential trace nutrients such as iron (stimulating primary productivity), but also become incorporated into organic aggregates that form high-density particles (the ballast effect) with faster sinking rates - thus accelerating the transfer of newly fixed carbon dioxide to the deep sea. The efficiency of this transfer determines the storage of carbon in the deep sea (after Ittekkot, 1993).

material intercepted at water depths of 2000 to 3000 m is consistently higher than that of the underlying surface sediments by at least a factor of 5 (Sirocko and Ittekkot, 1992) suggesting significant losses of C_{org} between deep-moored traps and sediments. These losses appear to be proportional to total material flux to the ocean's interior. The ultimate effect is that with increasing fluxes there is an increase in the amount of organic matter being remineralized in the deeper parts of the oceans. In other words, the storage of carbon in the deep sea via remineralization of organic matter and the particle fluxes are coupled processes, whereby an increase in deep-sea fluxes leads to increased carbon storage and consequently to a decrease in atmospheric CO_2-content.

19.7 GENERAL CONCLUSIONS

Sediment traps are the best presently available tools for studying particle fluxes linking processes at the sea surface with transport to the seafloor. They can collect samples continuously on hourly to yearly schedules. Fluxes measured during long-term experiments have recorded the signatures of all upper ocean conditions and processes. Potential problems to be addressed in association with sediment trapping are hydrodynamic bias, sample distortion by swimmers and decomposition. Use of natural tracers appears to be promising in resolving this issue.

The biogeochemical processes in the deep sea are coupled to atmospheric processes via particle flux in the ocean, the link being variations in the primary productivity in the upper ocean which exhibits strong spatial and temporal variability. To resolve the associated variability in the fluxes of biogeochemical elements to the oceans' interior, simultaneous long-term monitoring of the atmosphere and the surface ocean by satellite remote sensing, and of the deep sea by time-series devices such as sediment traps will be necessary.

The comprehensive elucidation of the factors controlling particle fluxes in the ocean further requires that investigations of oceanic processes be complemented with long-term data sets from the atmosphere and from the terrestrial environment. The latter exerts a strong influence on particle flux in the ocean both directly by providing particles and indirectly by stimulating marine biological processes. Investigations of dust fallout over the oceans, suspended matter and nutrient inputs from rivers and from continental margins have to be incorporated into programs designed to understand processes controlling particle flux in the oceans. The nature and magnitude of these inputs have been changing due to human activities. Also, they are likely to be affected by the projected regional and global climate changes.

The efficiency of the biological pump (organic carbon pump) in the ocean in sequestering atmospheric CO_2 is determined by the production and "rain ratio" of $C_{org}/C_{Carbonate}$. This, in turn, is determined by the production ratio of diatoms to coccolithophorids in the upper ocean. Increased diatom production tends to increase the ratios, and thus the efficiency of the biological pump. It is therefore important to understand the factors controlling the shifts in the upper ocean biological community structure and the variabilty of the component fluxes to the deep sea. Time-series measurements of particle flux in the ocean suggest that such shifts are related to the availability of silicate, the major limiting element for diatoms in the upper ocean. A better understanding of the interaction of the silica cycle with the cycles of other nutrient elements such nitrogen and phosphorus in the ocean will be crucial to assess the efficiency of the oceanic biological pump to sequester atmospheric CO_2.

Marine regions of interest for future research in this context are areas affected by nutrient inputs from upwelling water masses, continental margins, rivers and ice-melt. They receive an adequate supply not just of dissolved phosphate and nitrate but also of silicate. These are also regions which are likely to be affected by potential changes in ocean circulation, in precipitation and runoff, and in cryosphere components expected from a projected change in climate.

Particles settling to the seafloor carry environmental and climatic information to the deep sea. This information is likely to be modified and in some instances lost due to dissolution, decomposition and transformation reactions which occur during settling and/or at the sediment-water interface. The degree of preservation of these signals in sediments has to be investigated in order to assess their paleoceanographic use.

Particle flux in the ocean responds to climatic and environmental forcing. Therefore, oceanic particle flux studies have the potential to detect, monitor and help in reconstructing, global changes.

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