

7.9 ALTERATION OF SETTLING PARTICLES

Some biogeochemical components of the settling material to the ocean's interior are altered greatly; other components are not significantly altered. In general, CaCO_3 and lithogenic particles are well preserved even in calcite-under-saturated water, but organic matter is altered far more while settling through a water column. Biogenic SiO_2 is more susceptible to dissolution, but usually the mass does not decrease significantly within the bathypelagic water column.

At most of the deep ocean stations where sediment trap experiments were conducted, only a few percent of the labile matter or the labile portion of particles arrived in the ocean's interior; other portions were mineralized into solutions and returned to the water before reaching the abyssal layer. However, the majority of CaCO_3 (which occupies up to 60% of the settling particles in many deep oceans), all lithogenic particles, and about a third of the biogenic SiO_2 particles should arrive in the ocean's interior. In other words, about 75% of the particles which are produced in the upper oceans will arrive in the deep layers and on the ocean bottom.

7.9.1 INORGANIC CARBON: CaCO_3

At all stations in the North Atlantic, including a Nordic Sea station, CaCO_3 particle flux showed no evidence of decreasing with depth (Honjo, 1990a; Honjo and Manganini, 1993). In the North Pacific where the calcite compensation depth is as shallow as several hundred meters, the flux of CaCO_3 particles can decrease with depth; however, a limited number of depth-series measurement of CaCO_3 fluxes in the Pacific were not conclusive, differing by season, location and perhaps eddy effects. In the Gulf of Alaska, annual CaCO_3 flux at Ocean Station P decreased significantly with depth throughout a long-term time-series observation (Honjo, 1984) (Figure 7.8). On the other hand, at equatorial Pacific stations along 140°W , the calcite compensation depth is as low as approximately 400 m for example at $10^\circ\text{N } 140^\circ\text{W}$ (Takahashi, 1975). However, annual CaCO_3 fluxes did not decrease significantly with depth (Honjo et al., 1995). At a subtropical Pacific Gyre station, $15^\circ\text{N } 151^\circ\text{W}$, the CaCO_3 flux at 2.8 and 4.3 km was virtually the same, but decreased to 57% at 5.6 km although this non-time-series experiment lasted only 2 months in the autumn (Honjo, 1980). At a station at the great depth of 8.8 km in a Pacific trench, CaCO_3 flux decreased to a larger degree than at 4.3 km (Nozaki, 1986a); this subject will be elaborated later in this chapter.

If particulate inorganic carbon is produced proportionally to particulate organic carbon, primary production can be estimated from the flux of CaCO_3 which is not essentially influenced by depth in a CaCO_3 -saturated basin such as the North Atlantic. The ratio of primary production of organic carbon to inorganic carbon was estimated to be about 10 at the $48^\circ\text{N } 21^\circ\text{W}$ station (Goyet et al., 1990); the

inorganic carbon flux in the ocean's interior at this station was about 10 mole C; the estimated primary production during this time was about 100 mole C. This estimate coincides with the maximum estimation of primary production by other methods, including ^{14}C fixation method.

7.9.2 ORGANIC MATTER AND ORGANIC CARBON

Investigation of the processes of alteration and depletion of organic matter from settling particles, fresh to old, is critical in further understanding carbon cycles in the oceans. Various studies on many compound classes of organic matter including amino acids, amino sugar, protein, fatty acids, sterols and sugar compounds have begun to clarify their complex pathway and the rate of alteration of these materials while carbon compounds are transported through a water column (Wakeham et al., 1980; Lee and Cronin, 1984; Lee et al., 1983; Ittekkot et al., 1984a, b; Wakeham and Canuel, 1988; Handa, 1989).

Organic matter decreases at much higher rates than other particle classes because of the degradation process, particularly in the upper and mesopelagic layers. The export production of organic carbon and the nitrogen fluxes in the ocean's interior is theoretically the same as their new production; i.e., additional flux produced by resources other than recycled carbon and nitrogen (Eppley and Peterson, 1979). In general, fluxes of organic matter in the mesopelagic layer decrease in succession of two numerical modes: 1) exponential decrease in the upper-ocean layers; and 2) slow, linear-appearing decrease in the bathypelagic layers. This indicates that the rate of recycling is exponentially faster in the mesopelagic layers than in the deeper ones. Thus mineralized organic carbon in the upper ocean is allowed to return to the atmosphere within a relatively short time (on the order of minutes, hours or months). On the other hand, organic matter reaching the ocean's interior is unaltered while settling through the bathypelagic water column (deeper than 1 to 1.5 km) where the rate of remineralization is far smaller compared to the upper ocean. Organic carbon which arrives in the ocean's interior takes hundreds of years to recycle with atmospheric CO_2 .

One of the most desired capabilities for ocean science at present is the ability to estimate the flux of organic matter at any ocean depth relative to production in the euphotic layer (Suess, 1980; Broecker and Peng, 1982); many empirical models have since been proposed (e.g., Berger et al., 1987; Martin et al., 1987; Pace et al., 1987; Berger et al., 1989). Although such empirical equations are useful for the first order approximation of export production, because of seasonal complexity, none of these equations is sufficiently realistic to be applied universally (e.g., Honjo et al., 1982a; Haake et al., 1993).

The *E*-ratio, the percentage of flux in the ocean's interior of the total production at the upper surface, reflects the complex seasonal sequence of production,

changing mode of the removal process, and water column biogeochemistry as explained in this chapter. An *E*-ratio of organic carbon and nitrogen reflects the characteristics of settling organic matter, metabolism in the water column, particularly in the upper and mid layers, and the physical condition of the packaging of settling particles. Meantime, it is essential to further understand the spatio-temporal variability of global primary production.

To access the *E*-ratio of carbon (and other nutrients) is not an easy task, requiring the value of photosynthesized carbon as well as measurement of particulate organic carbon in the ocean's interior in the same area, both measurements in time-series, covering all seasons. A year-round variability of the *E*-ratio of organic carbon has been obtained along the 140°W transect of the equatorial Pacific; it varied from 0.2 to 0.6 during the El Niño season of 1990. When El Niño conditions temporarily disappeared in the latter part of that year, the ratio varied from almost zero to 1.4 (Figure 7.12) (Honjo et al., 1995). The *E*-ratio estimated from the time-series carbon fixation value taken from sediment-trap-collected organic carbon flux during the 1989 spring bloom at a North Atlantic station, 48°N 21°W, was 1.7 (Honjo and Manganini, 1993).

During the post-bloom period, zooplankton carapaces and their fragments are often removed from the upper layers to the deep layer. The sedimentation of gelatinous zooplankton carapaces which occurred in the summer and autumn of 1983 at Ocean Station P in the Gulf of Alaska provided a several-fold greater quantity of organic carbon flux than in a normal year (joint study with C.S. Wong, the Institute of Ocean Sciences, Sydney, BC, Canada; Honjo, 1990b). The large quantity of post-bloom zooplankton carapaces was exported to a depth of 1 km in the North Atlantic but apparently was rapidly regenerated before reaching the deep interior (Honjo and Manganini, 1993) (Figure 7.13); however this can also be attributed to the moving of the upper ocean source of supply.

In exceptional cases, for example, fluxes of organic matter increase at deeper layers. In the Panama Basin, the mass of combustible matter (organic matter plus indigenous water) increased in the layer below 2 km (Honjo et al., 1982a; Honjo et al., 1992). Combustible flux increased approximately 50% at 4 km compared to that at 2 km, although it decreased in the shallower layers. This was interpreted as an additional flux of organic matter which was supplied advectively from the near-by continental slope by re-suspended marine snow caused by the strong boundary current (Asper et al., 1992).

Less than 2% of dissolved nitrogen (NO_3) arrived at the 2-km trap at 48°N 21°W during the 1989 bloom. On an annual basis, the ratio of nitrogen and phosphorus in organic matter decreases with depth. However, such ratios also differ with locations and seasons. At the North Atlantic Stations, the C/N ratio at 1 km was often close to the plankton value (6.6) but increased to 8 at about 2 km and 8.5 and more at deeper layers. The C/N value remained low during the Atlantic bloom and significantly high during post-bloom episodes (Honjo and Manganini, 1993). The flux of phosphorus in organic matter is understudied and

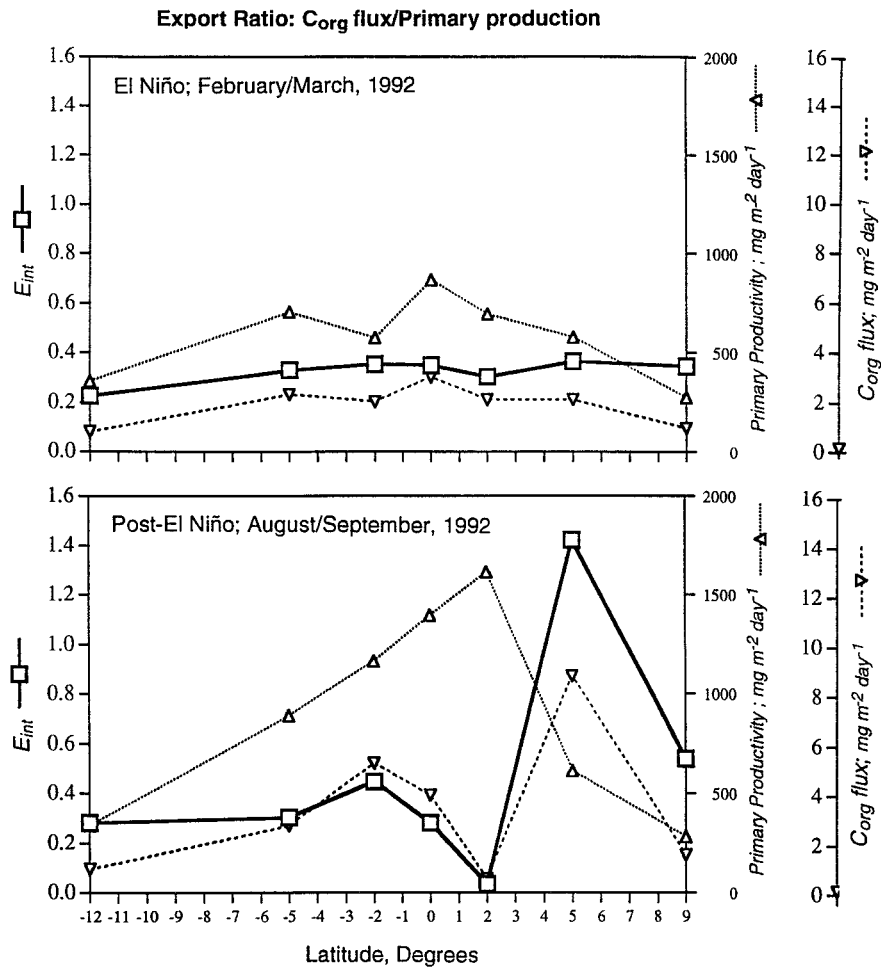


Figure 7.12 The export ratio of carbon to the ocean's interior (open squares; E_{int}) along 140°W, from 9°N to 12°S during February/March (upper panel: El Niño) and August/September (lower panel: post El Niño). Triangles represent primary productivity ($mg\ m^{-2}\ d^{-1}$) measured during the EqPac survey cruises (Murray et al., 1994), and inverted triangles depict organic carbon fluxes during the periods when primary productivity measurements were made.

not well understood. Phosphorus is strongly recycled in shallow water. Seasonal C/N/P values obtained from 34°N 21°W and 48°N 21°W are presented in Table 7.3, showing that, at these two stations, phosphorus among the three elements in settling particles decreases at the fastest rate.

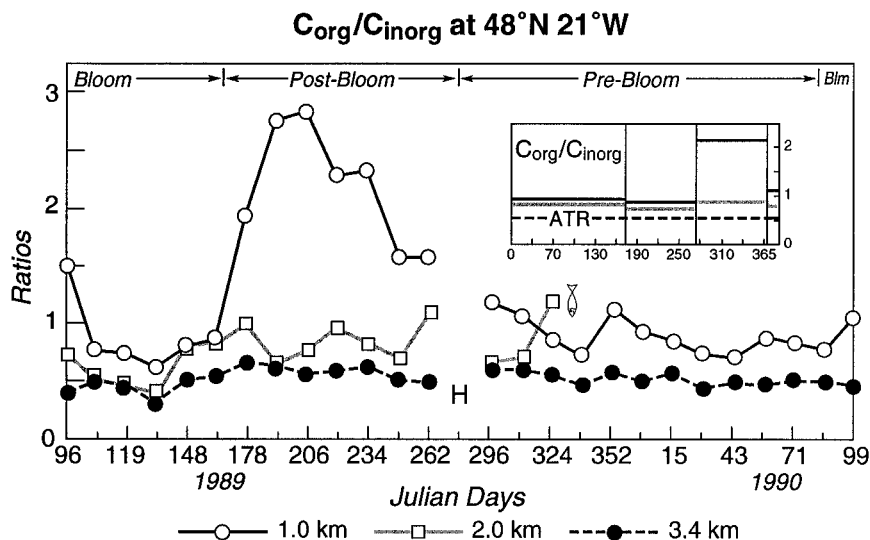


Figure 7.13 Vertical and temporal variability of the ratio of organic carbon to inorganic carbon at 48°N 21°W (NABE, Table 7.2) throughout a year, spring of 1989 to 1990. The ratio decreased with the depth and was consistently 0.5 (Attainable Terminal Ratio: ATR) at 3.4 km depth (insert) (Honjo and Manganini, 1993).

7.9.3 BIOGENIC SiO₂

The vertical flux of biogenic SiO₂ is complicated because of the irregular nature of mineralized tissue, which differs by taxa, compared to CaCO₃ tissue. Biogenic opal dissolves in the upper ocean (Nelson and Goering, 1977) as a function of water temperature (Hurd, 1983). For example, at 48°N 21°W about 27% of the dissolved SiO₂ which was converted to diatom frustules and radiolarian shells in the euphotic layer (0 – 52 m) arrived in the ocean's interior during the bloom. This amount was compared with the peak biogenic SiO₂ flux at 2 km which took place a few weeks later. The *E*-ratio of biogenic SiO₂, the ratio of production in the euphotic layer vs. flux in the ocean's interior, was thus estimated as 28% during the spring bloom (Honjo and Manganini, 1993) (Figure 7.8). This export ratio of biogenic SiO₂ partially supports previous ocean-chemical models which indicated about 30% of biogenic SiO₂ reaches the ocean's interior by escaping remineralization (Spencer, 1983).

The annual opal flux at 2 km during 1989 at this station was about 6 g m⁻² y⁻¹ (Honjo and Manganini, 1993), and is comparable to the lower end of the estimated flux derived from models, 7 to 12 g m⁻² d⁻¹ (Heath et al., 1976). Two thirds of the silicic acid is returned in solution to the surface and intermediate layers. The majority of stored SiO₂ generated by the bloom ought to be recycled to

Table 7.3 Ratios of biogenic carbon, nitrogen and phosphorus in settling particles at 3 depths relative to annual flux and fluxes during the bloom episode at 2 stations in the North Atlantic; 34°N 21°W and 48°N 21°W in 1989/90 (NABE, Table 7.2, Ref. 7). The total annual fluxes at these stations are given in Table 7.2 (Ref. 7). Details of bloom, pre- and post-bloom at these stations are explained in Honjo and Manganini (1993).

	34°N 21°W			48°N 21°W		
	C	N	P	C	N	P
Pre-Bloom						
1 km	53	8	1	49	6	1
2 km	99	12	1	63	8	1
D	153	17	1	89	10	1
Bloom						
1 km	40	6	1	101	15	1
2 km	148	19	1	136	19	1
D	154	18	1	177	23	1
Post-Bloom						
1 km	—	—	—	150	16	1
2 km	102	11	1	121	14	1
D	151	16	1	209	23	1
Annual						
1 km	47	7	1	96	12	1
2 km	128	16	1	120	16	1
D	154	18	1	148	18	1

the surface layer before the next annual bloom in order to keep the SiO₂ concentration at steady state. The rest is delivered to the ocean's interior and to the seafloor in the form of opal particles.

It seems that biogenic SiO₂ dissolves in two ocean zones. One is in the upper layers where dissolution is controlled by temperature and occurs quickly, on the scale of days to weeks. The diatom frustule flux and the species assemblage did not change significantly while settling from the 2-km to 3.7-km depth at this station (Honjo and Manganini, 1993), indicating that once biogenic opal reaches the ocean's interior, it does not further dissolve but arrives at the deep seafloor intact. Part of the reason would be that the majority of frustules are protected within fecal pellets (Schrader, 1971), though frustules, particularly centric frustules, are more pulverized in metazoan fecal pellets. However, sediment in the north-central Atlantic, including at the 48°N 21°W station, is carbonate-rich and low in opal, usually only a few percent (Lisitzin, 1972). It is reported that species diversity of radiolaria drastically decreased in bottom sediment at a tropical Atlantic site, from over 400 species in the trap to merely a dozen in the sediment below (Takahashi, 1991). Some suspect that the diatom frustules in the North Atlantic are generally less silicified, and that settling frustules are dissolved in the

upper and intermediate layers at a higher rate than in other ocean settings (Berger, 1976). Nevertheless, major dissolution should occur at the ocean bottom which is not constrained by water temperature.

7.9.4 VERTICAL INCREASE OF LITHOGENIC PARTICLE FLUXES

Studies of lithogenic matter in settling particles have found that the export of lithogenic particles to the ocean's interior is not simply constrained by the rate of fallout at the ocean's surface, as was envisioned by researchers. The main claim regarding lithogenic particle flux is its increase with depth (e.g., Honjo et al., 1982b; Masuzawa et al., 1989; Tsunogai et al., 1990). For example, a sediment trap deployed in the deep layers at 34°N 21°W collected approximately 2.2 g m⁻² of lithogenic particles per year in 1989 to 1990. This station was located at the edge of the trade winds where lithogenic particles are effectively transported. At 48°N 21°W, where no significant supply of airborne lithogenic particles is feasible, a relatively large lithogenic flux, 1.3 g m⁻² y⁻¹, was observed in the deep ocean layers. At both stations the Al flux (which usually represents the lithogenic component) increased linearly with depth through the meso- and bathypelagic layers (Figure 7.14). The increase of lithogenic flux is independent from the total flux which also often increases with depth. Therefore the meso-scale eddy diffusion model (Siegel et al., 1990) does not explain vertical increase of lithogenic particles which requires sources which supply refractory particles advectively.

7.9.5 PARTICLE FLUX IN THE INTERIOR OF THE VERY DEEP OCEAN TRENCHES IN THE PACIFIC

The deep trench system provides a natural laboratory for studying settling particles through a very long water column - as long as 9 km and even more. A set of samples collected by sediment traps set throughout such a very deep water column provides amplified information compared to a "normal" deep water column of 3 to 4 km - demonstrating chemical modification of particles, particularly by *in situ* dissolution and remineralization of CaCO₃, SiO₂ and organic matter, as well as scavenging of radionuclides and surface reactive elements. For example, the degree of under-saturation of CaCO₃ in the deep trenches in the North Pacific is the greatest in the world ocean (CFS level of 0.5; Takahashi, 1975).

Settling particles were first successfully collected from the interior of the Japan Trench (Sagami Trough) at a trap depth of 8.8 km (400 m above the bottom). They were compared with samples from a 4.3-km trap which was moored at a location equivalent to the depth of the rest of the basin. Even at such a great depth, near the deepest part of the world's ocean, hazardous anthropogenic radionuclides such as ²³⁹Pu, ²⁴⁰Pu and ¹³⁷Cs were found in settling particles (Nozaki, 1986). From the 8.8-km trap, a suite of palynomorph, including fungal, fern

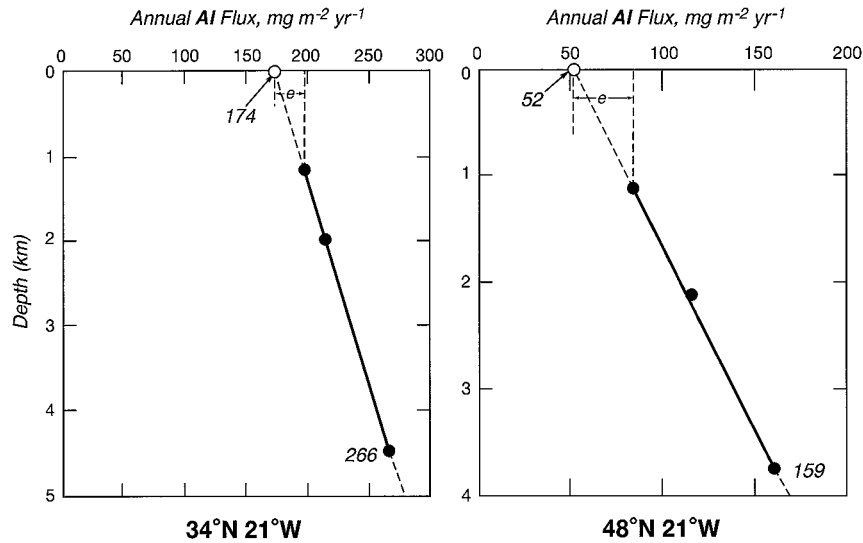


Figure 7.14 Plots showing the increase of lithogenic flux with depth at the 34°N 21°W and 48°N 21°W stations. Extrapolation to the surface allows an estimation of aeolian input (white circles). Dashed lines in the Figures indicate maximum and minimum estimates of aeolian input. The difference between these estimates, denoted as e , suggests an uncertainty of roughly 20% in the estimate of aeolian input.

spores, dinoflagellates, et cetera, were found; also found were pollens from pine and cedar (Matsuoka, 1989). The sedimentational route of pollen from the atmosphere to a depth of 8.8 km warrants further study since some pollen is virtually unsinkable in water (Traverse, 1988).

The flux of CaCO_3 in the 8.8-km trap was, compared to the 4.3-km trap, significantly less, and the surfaces of foraminifera tests were more extensively corroded. Biogenic SiO_2 was also less, but not to the same degree as CaCO_3 . Seventy percent of the 8.8-km samples consisted of lithogenic particles; their flux surged sporadically, indicating that they were supplied by turbidite activity in the trench (Nozaki, 1989a). This technically challenging program has been continued from 1982 to the present (Dr. Y. Nozaki, pers. comm., 1994).

7.10 SEASONAL AND GEOGRAPHIC VARIABILITY

7.10.1 PARTICLE FLUXES IN THE MARGIN

Particle flux to the deeper layers, specifically the production, regeneration and burial of organic matter in a margin environment, plays a major role in the global carbon cycle (e.g., Walsh, 1988; Berger et al., 1989; Milliman, 1993). Light has begun to be shed on the transportation of particles from shelves and slopes to the ocean's interior, but this warrants further study (e.g., Thunell et al., 1994a; Biscaye et al., 1994a, b). Particle behavior in the margin environment seems to be, undeservedly, understudied. However, as the title of this chapter indicates, I am not well qualified to elaborate on this large area of ocean studies and will not do so in this review. Shelf and upper slope areas are far more active with regard to primary production, high velocity water movement, and are, in general, unstable, high energy environments compared to the ocean's interior.

Primary productivity in the margins is $250 \text{ gC m}^{-2} \text{ y}^{-1}$, in a rough average, which is about 10 times greater than in the open seas (Berger et al., 1989). Organic matter which is vigorously recycled by the large ecosystem continues to the bottom boundary and into the sediment. However, because of the high burial rate, the role of the margin environment as a carbon sink is still very high (e.g., Walsh et al., 1981; Romankevich, 1984). Carbon fluxes measured by long-term sediment trap experiments in the San Pedro Basin were about $12 \text{ gC m}^{-2} \text{ y}^{-1}$ (Thunell et al., 1994) and the fluxes on the Middle Atlantic Bight near the bottom of the shelf were $28 \text{ gC m}^{-2} \text{ y}^{-1}$, and $32 \text{ g m}^{-2} \text{ y}^{-1}$ along the slope (Andersen et al., 1994). Wassmann and Slagstad (1990) estimated particle flux in the central Barents Sea as $24.6 \text{ gC m}^{-2} \text{ y}^{-1}$. These values are one or two orders of magnitudes larger than the rate of carbon export to the ocean's interior (Table 7.2).

The Middle Atlantic Bight study (SEEP-II Project) found no evidence to support the hypothesis that biogenic particles settling to the interior of the margin environment are re-exported to the deep ocean environment; but it appears that they are consumed *in situ* (Biscaye and Anderson, 1994). This is contrary to an established view of material being exported from the margin to the basin (e.g., Walsh, 1988, and some field results such as at Cape Hatteras, Walsh, 1994). Such contradiction may indicate the complex individualization of a margin environment in general. For example, export of re-suspended marine snow particles from the shelf edge to the deep basin has been observed by a marine snow camera off Cape Hatteras where the Gulf Stream hits the shelf edge (Asper et al., 1992), and a large intermittent slide of the bottom brine layer containing a large amount of fresh organic carbon ("winter burst") was caught by time-series sediment traps in the northern Barents Sea during mid winter using natural radionuclides as tracers (Honjo et al., 1988) (Figure 7.15). Narita et al. (1990) estimated the amount of time necessary for particles settled in shallow areas of the East China Sea to be transferred to the interior of the Okinawa Trough (1.9 km deep) to be approximately 16 years.

7.10.2 CONTRAST BETWEEN AND IN THE GLOBAL BASINS

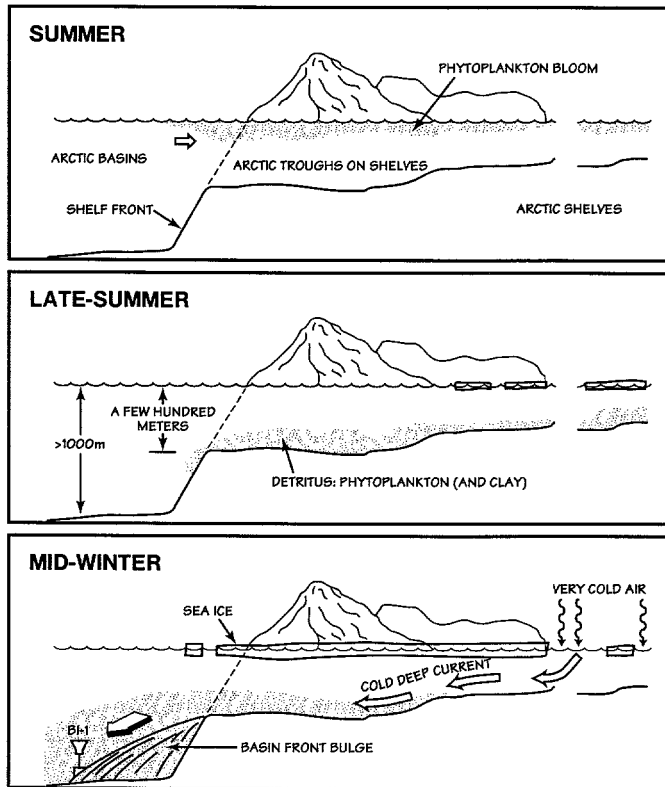
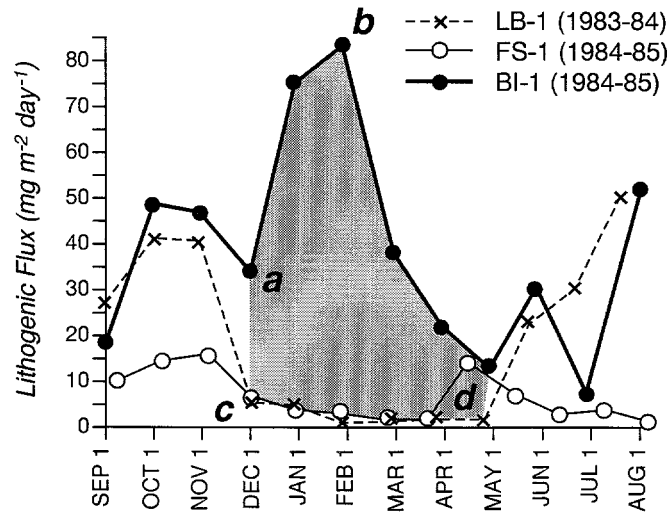
Processes for removal and transport of particles and their biogeochemically essential constituents have been clarified by detailed studies at a number of stations. The main sources of errors in measuring particle fluxes, the amplitude of inter-annual difference as well as the eddy effect to the vertical fluxes, have begun to be understood. However, before we reach generalizations regarding the mode of particle fluxes in the world ocean and to further understand the role of settling flux in a global context, more geographic coverage by long-term trap deployment is warranted to represent not only the latitudinal ocean zones but also the major marginal seas.

Nevertheless, global efforts to deploy many time-series sediment trap moorings at strategic locations in the ocean's interior covering all seasons as well as inter-annual periods have begun to reveal some fundamental contrasts in biogeochemical functions between major oceanic regions (Honjo, in preparation). For example, organic carbon fluxes in the interior of the North Pacific ($>1 \text{ g m}^{-2} \text{ y}^{-1}$) are generally larger than in the interior of the North Atlantic ($<1 \text{ g m}^{-2} \text{ y}^{-1}$). The flux of inorganic carbon reverses this trend; more CaCO_3 is transported to the interior of the North Atlantic than the North Pacific. Biogenic SiO_2 fluxes in the North Pacific are several times larger than in the North Atlantic; the $\text{Ca/Si}_{\text{bio}}$ ratio is >1 in the North Atlantic and <1 in the North Pacific. The former can be called a "carbonate ocean" and the latter a "silica ocean". An extreme representation of a silica ocean is the Weddell Sea where only a trace of CaCO_3 was exported, but where the flux was overwhelmed by diatom frustules (Fischer et al., 1988). The equatorial Pacific Ocean seems to be independent from the rest of the Pacific; it is a strongly carbonate ocean with a high $\text{Ca/Si}_{\text{bio}}$ ratio; $\text{C}_{\text{org}}/\text{C}_{\text{inorg}}$ is within the same range as in the North Atlantic; and the flux of organic carbon in the interior is about a half that of the North Pacific (Honjo et al., 1995). Another difference between the North Atlantic and North Pacific is that the majority of annual particle export in the former is done during a bloom while in the boreal Northern Pacific no seasonally defined bloom similar to that of the North Atlantic has been observed (Table 7.2).

7.10.3 SEASONAL AND INTERANNUAL VARIABILITY OF PARTICLE FLUXES

It is understood that particle fluxes in the interior of any ocean change by season. The contrast in flux between the bloom- and slack-time observed in the ocean's interior is strong; in many oceans, the ratio between the highest and lowest yearly fluxes is as large as more than 100. It seems that the equatorial Pacific is the only exception so far known where fluxes change relatively little throughout a year (Figure 7.16) (Honjo et al., 1995). The constituents of settling particles also change, reflecting the ecological sequence in the surface ocean. Specifically, the content of CaCO_3 and biogenic SiO_2 changes with time and location. The oceanic

forcing which causes such variability is beginning to be understood, but this subject warrants further study. For example, the strong annual variability of the



flux in the Arabian Sea has been explained by the evolution of the NE and SW monsoons, the processes of upwelling and the removal of carbon accelerated by mineral aerosol fallout with intensified wind (Nair et al., 1989; Ittekkot, 1991; Curry et al., 1992; Haake, et al., 1993; this volume).

Our understanding of interannual variability of particle export in the ocean's interior is limited to several stations. At a Bermuda time-series station (this volume, Chapter 9) and at a station in the Gulf of Alaska (C.S. Wong, pers. comm.) decadal information has been gathered. Also at 6 stations across the Arabian Sea and the Bay of Bengal, sediment trap moorings have been maintained for almost 10 years (Ittekkot, 1991; Haake et al., 1993; this volume, Chapters 14 and 15). To the north and east of Iceland, two long-term sediment trap stations have been maintained for several years (J. Olafsson and D. Ostermann, pers. comm.). Three new long-term time-series sediment trap stations/transects have been recently initiated near Hawaii (D. Karl, pers. comm.), in the Okinawa Trough (M. Honda, pers. comm.) and the South China Sea (this volume, Chapter 16). The results so far suggest that the total fluxes and the fluxes of the main constituents of settling particles change on the order of a factor which corresponds to the interannual changes of forcing events such as monsoons, El Niño and intertropical convergence.

7.10.4 NORTH ATLANTIC AND NORTH PACIFIC

The bloom-type sequence export of particles from the euphotic layer to the interior appears to be commonly found in the temperate and subarctic North Atlantic. At the 34° 21'W and 48°N 21'W stations, more than half of the particle export depends on a single bloom. The onset of this bloom is delayed with increase in latitude; the bloom peak at 34°N was in late February to early March, while at the 48°N station it was delayed to May (Honjo and Manganini, 1993). When the bloom reaches as far north as the Lofoten Basin, about 69°N, the main peak appears as late as September/October (Honjo, 1990). In the Norwegian Current area of the Nordic Seas the bloom is much broadened, but essentially follows the same sequence; however, the length of bloom is longer than in southern zones (Honjo, 1990a; G. Wefer, pers. comm.).

Figure 7.15 Upper panel: A large flux, particularly of lithogenic particles during mid-winter, was observed at a 2-km-deep slope station near a large shallow fjord along the west coast of Spitsbergen (Bear Island, Table 7.2). The "winter burst" contains a high percentage of organic carbon. The comparison of two offshore basin stations located near-by did not show such mid-winter increase of fluxes (Honjo et al., 1989). Lower panel: a schematic explanation of winter burst. The phytoplankton bloom during summer was not all grazed and consumed because of the early arrival of winter. There is a large supply of glacial lithogenic matter and organic matter deposits at the bottom of the fjord. The cold brine is generated during winter and flows along the bottom of the fjord (the continental slope is as deep as 2 km), it carries with it fresh organic-rich sediment (Honjo, 1990).

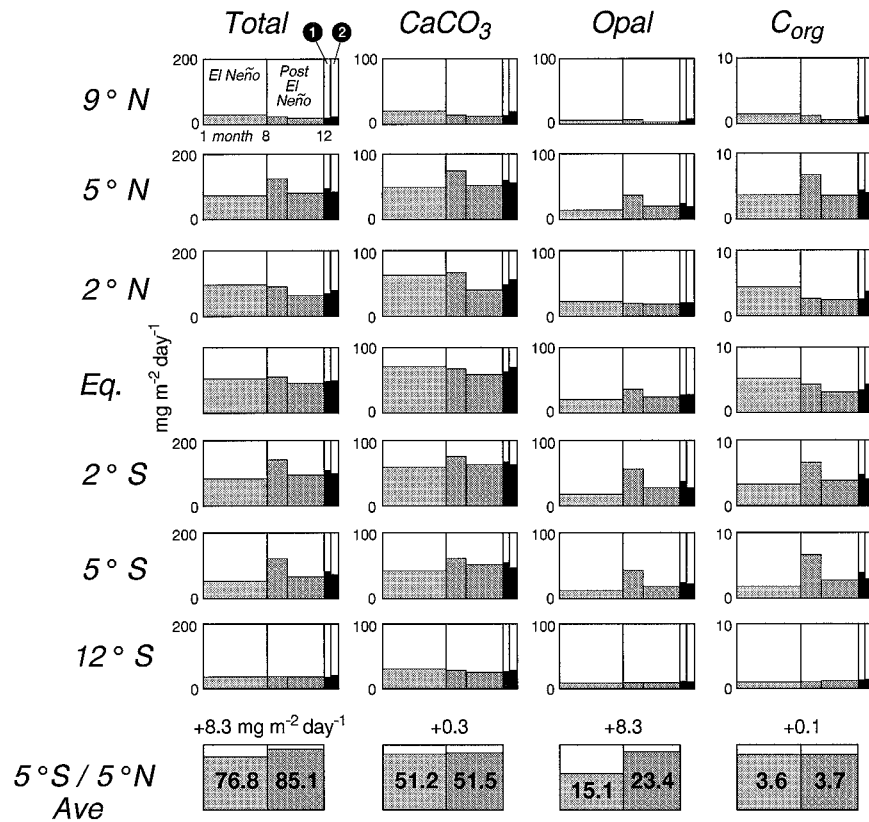


Figure 7.16 Total CaCO₃, biogenic SiO₂ and organic carbon flux (mg m⁻² d⁻¹) at each EqPac station. (Table 7.2). Each box is divided into El Niño and post El Niño, 1992. Post El Niño is separated into instability wave periods (middle of the box) and the later periods. The two narrow dark columns on the right indicate: 1) post El Niño average and 2) annual average. At the bottom line, the grand average of fluxes (mg m⁻² d⁻¹) from the 5°N to 5°S stations during El Niño and post El Niño are compared (Honjo et al., 1995).

The export of particles to the interior of the northwestern Pacific consists of a significantly larger annual biogenic SiO₂ flux than the northeastern Pacific/Gulf of Alaska (Tsunogai and Noriki, 1991). These authors explained this difference by the former being bloom-type production, and the latter upwelling-type production. Time-series trap experiments in the Gulf of Alaska, Bering Sea and the Sea of Okhotsk all show that the succession of exports begins with a massive flux of biogenic SiO₂ with diatom frustules in the spring. CaCO₃ (inorganic-carbon) particle blooms appeared in the autumn and sometimes continued to late November, often separated by a summer flux slack. The Sea of Okhotsk is an extreme exam-

ple where large fluxes of biogenic SiO_2 in the spring and CaCO_3 flux in the autumn are clearly separated by a brief cessation of flux in mid to late summer (Figure 7.17). In contrast, as previously described, the biogenic SiO_2 and CaCO_3 export events are not separable in the North Atlantic bloom (e.g., Figure 7.8).

In general, the ratio between CaCO_3 and biogenic SiO_2 in the higher-latitude North Pacific is far smaller than in the North Atlantic, north of 34°N . This is attributed to the lack of spring diatom bloom in the North Atlantic. The annual organic carbon flux is generally larger in the North Pacific compared to the North Atlantic (Table 7.2). This also can be explained as the organic carbon flux in the North Pacific being associated with the high export event of biogenic SiO_2 in the spring. However, in the North Atlantic, organic carbon appears to be associated with calcium carbonate which is dominant in this basin.

7.10.5 PACIFIC AND ATLANTIC SOUTHERN OCEAN

In the southern Pacific Ocean at 61.5°S 150°E , south of the Antarctic Convergence Zone, at a station about 3.8 km deep, Tsunogai et al. (1986) measured biogenic particle flux as large as $2.5 \text{ g m}^{-2} \text{ d}^{-1}$ from January 4 to 14, 1984. Fluxes during the other periods of the austral summer were approximately $1 \text{ g m}^{-2} \text{ d}^{-1}$. Although the trap was deployed only about 2 months during the maximum austral summer, the estimated minimum of the annual flux was $69 \text{ g m}^{-2} \text{ d}^{-1}$ - comparable to the annual flux in the interior of the Bering Sea. Similar to the Weddell Sea, the majority of collected particles were biogenic SiO_2 , as high as 78%, with only 2% of CaCO_3 . However, the total annual flux in the Weddell Sea was only $0.4 \text{ g m}^{-2} \text{ y}^{-1}$ during 1985 (Fischer et al., 1988).

The highest seasonal contrast in particle flux was found in the Bransfield Strait, Antarctic Peninsula, at 1.6 km deep, during a multi-year, time-series trap experiment (Wefer, 1989), where an enormous flux of biogenic particles, as large as about $1 \text{ g m}^{-2} \text{ d}^{-1}$, was observed for a few weeks during the maximum austral summer; the flux virtually died off during the rest of the year. The total particle flux in this year was $109 \text{ g m}^{-2} \text{ y}^{-1}$ (about 50% was lithogenic particle flux) which is larger than any other ocean flux so far recorded. Like the fluxes from the other southern stations, the majority of the biogenic flux was biogenic SiO_2 with a small CaCO_3 flux (Wefer et al., 1988), showing a strong contrast from the biogeochemical characteristics of settling particles in the Nordic Sea which is dominated by CaCO_3 (Honjo, 1990), but similar to areas of the northwestern Pacific such as the Bering Sea (Table 7.2).

In the northern Weddell Sea, the variability of particle fluxes was controlled by the regression of the ice edge. The flux was concentrated within the few months of the austral summer, and there was virtually no flux during the ice-fast period. The annual flux was extremely small compared to any other time-series stations dis-

cussed in this chapter ($0.4 \text{ m}^{-2} \text{ y}^{-1}$ in 1986) and, noticeably, CaCO_3 flux was only a trace amount, as at all other Southern Ocean stations (Fischer et al., 1988).

7.10.6 EQUATORIAL PACIFIC

The annual succession of particle export in the equatorial Pacific (EqPac) differs significantly from the other regions studied so far. The equatorial Pacific is a zone on both sides of the equator, about 10° both to the north and south, characterized by latitudinal boundary conditions set by the equatorial current and counter current systems which interlace with equatorial meridional instability waves. Vigorous upwelling along the equator induced by the trade winds results in a high rate of production. When the trade winds stall and upwelling stops, the open ocean ecosystem becomes less productive and El Niño conditions prevail. From the results of an extensive sediment trap array experiment conducted between 9°N and 12°S , along 140°W (Figure 7.2), in 1991, which began as a mild El Niño year and then resumed post El Niño conditions (Murray et al., 1994), the evolution of particle sedimentation was observed with reference to the succession of the strength of trade winds and other conditions. In the Panama Basin in the easternmost equatorial Pacific environment, particle fluxes are strongly influenced by the behavior of the Intertropical Convergence Zone, differing significantly between windy, wet periods and dry, relatively calm periods (Honjo, 1982).

When upwelling along the equator resumed in the summer of 1991 and the ocean was then in a post El Niño condition, more biogenic material was produced, the productive zone spreading to both sides of the equator by equatorial instability waves. During post El Niño, more biogenic SiO_2 and organic carbon is exported than during the earlier half of the year (Figure 7.16). During a non El Niño year, compared to an El Niño year, more vigorous upwelling as well as more active tropical instability waves occur along the equator. This enhances export of biogenic SiO_2 to the interior of the equatorial zone (Dymond and Collier, 1988). However, CaCO_3 was consistently exported, regardless of the El Niño conditions, and the ratio of CaCO_3 to biogenic SiO_2 was always large. Thus the ratio of organic carbon to inorganic carbon became smaller; this discourages the notion that this large productive ocean is an effective sink of atmospheric CO_2 .

7.11 SUMMARY AND CONCLUSIONS

In order to understand the biogeochemical cycle of matter in the sea, it is crucial to investigate ocean particle flux in order to find the missing link which connects material flowing from the surface to the ocean's bottom. Settling particles are critical in the transfer of energy, nutrients from the sun-light filled surface, to the abyssal ocean floor several thousand meters below. The biological pump catches atmospheric CO_2 and sends it down through the ocean's layers in the form of organic carbon. Only a small percent of organic matter produced in the upper ocean arrives in the ocean's interior, and the amount of carbon contained in settling particles exported to the ocean's interior is equivalent to the quantity of

carbon which is removed from atmospheric CO₂. Therefore, assessing organic carbon flux in the ocean's interior and clarifying the process of this organic-carbon export is crucial to understanding the fate of fossil-fuel CO₂.

In order to use microfossil assemblages in the seafloor sediment to reconstruct the glacial and interglacial environment of the earth, information must be ascertained regarding how present-day counterpart organisms arrive on the ocean floor, are collected by a sediment trap (biocoenosis), and adjust to ocean conditions. In order to establish a proximity link, it is necessary to gather atmospheric, air-sea interface and upper-ocean hydrographic information.

At this time, in order to meet the above objectives of understanding biogeochemical cycles, time-series sediment traps deployed with bottom-tethered moorings are one of the best approaches to collecting settling particles in the ocean's interior. Time-series, synchronized sediment trap arrays which are deployed over a long period have proven to be an efficient tool to attack a wide range of particle flux problems. Recent introduction of large, basin-scale arrays has assisted understanding of the impact of atmospheric forcing on biogeochemical cycles in the ocean by, for example, such events as seasonal monsoons and El Niño. Importantly, sediment trap experiments continued for more than one year in all ocean depths have begun to provide us with "total annual flux", covering all seasons, and, for the first time, have permitted us to match particle flux information with the paleoceanographic time scale and information on the temporal variability of the ocean particle fluxes. Uncertainties regarding the efficiency of a sediment trap still need to be constrained. However, traps deployed in the deep ocean perform better because the deep ocean is less energetic and the levels of biological activities are low. Perhaps the most important problem to be solved is the effect of mesoscale eddy diffusion which results in the apparent variability of vertical fluxes at the same mooring site.

Time-series collection of particle fluxes from many mooring locations, distributed throughout all major basins and marginal seas, has revealed a surprisingly large degree of seasonality. In the North Atlantic stations, particle fluxes in the ocean's interior responded to the rapid increase of surface productivity during the spring bloom with a short delay in the export of the major portion of annual flux. On the other hand, total particle fluxes in the equatorial Pacific changed little throughout the year; only biogenic SiO₂ and organic carbon fluxes were controlled by upwelling along the equator. In the northern Pacific a very large variability of biogenic SiO₂ flux was observed. In the Arabian Sea two monsoon phases, SW and NE wind-forcing, essentially controlled the flux to the interior. Knowledge of time-series variability of fluxes in the ocean's interior allows us to reconstruct the ecological sequences which have evolved in the upper layers. In areas where we have deployed year-round sediment traps (except for the deep polar regions) organic carbon flux in the ocean's interior ranges from 0.3 to 1.8 g m⁻² y⁻¹ (Table 7.2).

We have begun to understand the processes of removal of biogenic matter from the upper ocean to the interior. An important contribution of the last two decades with regard to the ocean's biogeochemical cycle is the re-confirmation of the hypothesis that the upper ocean and the ocean's interior are linked by "settling particles" which are biologically mediated aggregations of upper-ocean-generated particles which settle at speeds that are orders of magnitude faster than the descending rate of individual fine and light particles. Arrays of traps, distributed at vertical distances, with their open/close timing synchronized, have provided data on the bulk residence time of settling particles in water columns; this was estimated as 100 to 200 m d⁻¹.

Taking advantage of this rapid transportation, nearly all CaCO₃ particles arrive in the deep ocean, even when it is under-saturated with calcite in the very deep layers below 6 km. An experiment in the Atlantic showed that about two-thirds of biogenic SiO₂ is dissolved in the upper layers, the remainder entering the ocean's interior. The flux of lithogenic matter, a minor constituent but important as a ballast of settling particles, often increases with depth. About three quarters of the particles which are produced in or enter at the upper layers arrive in the ocean's interior.

Only a small percentage of organic matter successfully descends with settling particles as far as the ocean's interior. If the downward removal of particulate organic matter from the euphotic layer ceases, the oceanic biological pump will stop. But organic particles are often lighter than sea water. Therefore, a critical mechanism for maintaining the carbon cycle in the open ocean is the ballasting of settling particles, enabling them to sink through ocean layers. The majority of settling organic matter is remineralized or dissolved while settling through the upper and middle layers. To maintain a steady-state DOM level, dissolved organic matter which is supplied to the upper oceans must be recycled to the euphotic layer within one year - or the time between the spring bloom of one year and the spring bloom of the next.

7.12 OUTLOOK

Deep-ocean time-series sediment trap and associated deployment technology is functioning well. To constrain the instability of vertical particle fluxes caused by mesoscale eddy diffusion is the immediate problem to attack at individual sites. The data we have so far gained fall short of constraining the variability of export fluxes and their relationship to surface productivity and other ocean data. In order to assess the variability of export flux of organic carbon and other biogeochemically critical particles in time and space, particularly in the ocean's interior, regional and basin-wide deep-sea sediment-trap experiments should be further conducted with international cooperation.

The geographical scale of sediment trap arrays must be expanded to a global scale. Larger-scale synchronization of trap opening/closing such as is presently conducted (or planned to be conducted) from the Bering Sea to the Arabian Sea (in order to cover the propagation of seasonal monsoons) should also cover the world's oceans. Particle fluxes in the high-latitude oceans and marginal seas and their relationship to the deep basins must also be attacked.

Detailed process studies of ocean particles must be continued at as many stations as possible, to represent each ocean setting, in order to constrain the information link between the air, upper ocean, ocean's interior and the deep-sea floor. Biocoenosis studies must be further developed on all major taxa to better establish paleoproximity functions. Other atmospheric and oceanographic criteria including long-term meteorology, air-sea interface, continuous ocean color sensing, satellite observation of sea surface temperatures, ship-board measurement of productivity, plankton ecology, salinity, thickness of mixed layers and nutrient concentration should be measured to establish proximity. Deployment of meteorological buoys with relevant sensors and long-term time-series trap arrays is recommended.

7.13 ACKNOWLEDGMENTS

This paper is based on my overview talk entitled "Perspectives in Ocean Biochemical Flux Studies" which was read at the SCOPE/UNEP workshop on Particle Flux in the Ocean, sponsored by the United Nation's Environmental Programme, at the University of Hamburg, on September 20, 1993. I very much appreciate the encouragement from Prof. Venugopalan Ittekkot, the convenor of the workshop and valuable discussions and suggestions from the participants. I thank all my international colleagues who have worked with JGOFS and the High Latitude Ocean Flux Program. Steven J. Manganini and I have collaborated since the inception of our global particle flux program, the PARFLUX Program, at Woods Hole Oceanographic Institution. Many of the findings and interpretations in this article are the result of constant field collaborations and discussions with him. I am also grateful to Ken Doherty who has developed many advanced tools to investigate ocean particle fluxes. I am grateful for their insights and generosity in allowing their presentation here. Also I thank Katherine Brown for her great effort in editing this manuscript.

This research was supported by the National Science Foundation, Arlington, Virginia, under grant # OCE 9311199 and the High-Latitude Ocean Flux study was supported by the Office of Naval Research, Arlington, Virginia, under grant N00014-89-J-1288. I sincerely thank them for their persistent encouragement and sponsorship of global particle flux research. This is Contribution No. 168 of JGOFS and No. 9006 from Woods Hole Oceanographic Institution.

7.14 REFERENCES

- Allredge, A. L. (1976) "Discarded appendicularian houses as sources of food, surface habitats, and particulate organic matter in planktonic environments", *Limnol. Oceanogr.*, **21**, 14–23.
- Allredge, A. L. and Gotschalk, C. (1988) "In situ settling behavior of marine snow", *Limnol. Oceanogr.*, **33**, 339–351.
- Allredge, A. L. and E. O. Hartwig (eds) (1986) *Aggregate Dynamics in the Sea*. Workshop report, Office of Naval Research, American Institute of Biological Sciences.
- Allredge, A. L. and M. W. Silver (1988) "Characteristics, dynamics and significance of marine snow", *Prog. Oceanogr.*, **20**, 41–82.
- Altabet, M. A., W. G. Deuser, S. Honjo and C. Stienen (1991) "Seasonal and depth-related changes in the source of sinking particles in the North Atlantic", *Nature*, **345**, 136–130.
- Anderson, R. F., M. P. Bacon, P. G. Brewer (1983) "Removal of Th-230 and Pa-231 from the open ocean", *Earth Planet. Sci. Lett.*, **62**, 7–12.
- Anderson, F. A., G. T. Rowe, P. F. Kemp, S. Trumbore and P. E. Biscaye (1994) "Carbon budget for mid-slope depocenter of the Middle Atlantic Bight", *Deep-Sea Res.*, **4**, 669–703.
- Asper, V. L. (1987) "Measuring the flux and sinking speed of marine snow aggregates", *Deep-Sea Res.*, **34**, 1–17.
- Asper, V. L., S. Honjo and T. H. Orsi (1992) "Distribution and transport of marine snow aggregates in the Panama Basin", *Deep-Sea Res.*, **39**, 939–952.
- Bacon, M. P. (1988) "Tracers of chemical scavenging in the ocean: Boundary effects and large scale chemical fractionation", *Philosoph. Trans. Roy. Soc. London, A*, **320**, 187–200.
- Bacon, M. P., D. W. Spencer and P. G. Brewer (1976) " $^{210}\text{Pb}/^{226}\text{Ra}$ and $^{210}\text{Po}/^{210}\text{Pb}$ disequilibria in seawater and suspended particulate matter", *Earth Planet. Sci. Lett.*, **32**, 227–296.
- Bacon, M. P., C.-A. Huh, A. P. Fleer and W. G. Deuser (1985) "Seasonality in the flux of natural radionuclides and plutonium in the deep Sargasso Sea", *Deep-Sea Res.*, **32**, 273–286.
- Baker, E. T., H. B. Milburn and D. A. Tennant (1988) "Field assessment of sediment trap efficiency under varying flow conditions", *J. Mar. Res.*, **46**, 573–592.
- Berger, W. H. (1976) "Biogenous deep sea sediments: Production, preservation and interpretation", in J. P. Riley and R. Chester (eds) *Chemical Oceanography*, 2nd Ed., Vol. 5, Academic Press, London and New York, 265–388.
- Berger, W. H. and D. Piper (1972) "Planktonic foraminifera: differential settling dissolution and redeposition", *Limnol. Oceanogr.*, **17**, 275–287.
- Berger, W. H., K. Fisher, C. Lai and G. Wu (1987) "Ocean carbon flux: Global maps of primary production and export production", in C. Agegian (ed) *Biogeochemical Cycling and Fluxes between the Deep Euphotic Zone and Other oceanic Realms*, NOAA Symp. Ser. for Undersea Research, NOAA Undersea Research Program, vol. 3(2). Preprint in SIO ref. 87–30.
- Berger, W. H., V. S. Smetacek and G. Wefer (1989) "Ocean productivity and paleo-productivity - an overview", in W. H. Berger, V. S. Smetacek and G. Wefer (eds), *Productivity of the Ocean: Present and Past*, John Wiley & Sons, Chichester, 1–34.
- Berner, R. A. and S. Honjo (1981) "Pelagic sedimentation of aragonite: Its geochemical significance", *Science*, **211**, 940–942.

- Betzer, P. R., W. J. Showers, E. A. Laws, D. C. Winn, G. R. DiTullio and P. M. Kroopnick (1984) "Primary productivity and particle fluxes on a transect of the equator at 153°W in the Pacific Ocean", *Deep-Sea Res.*, **31**, 1–11.
- Biscaye, P. E. and R. F. Anderson (1994) "Fluxes of particulate matter on the slope of the southern Middle Atlantic Bight, SEEP-II", *Deep-Sea Res.*, **41**, 459–509.
- Biscaye, P. E., C. N. Flagg and P. G. Falkowsky (1994a) "The shelf edge exchange processes experiment, SEEP-II: An introduction to hypotheses, results and conclusions", *Deep-Sea Res.*, **41**, 231–252.
- Biscaye, P. E., G. T. Csanady, P. G. Falkowsky and J. J. Walsh (1994b) "Shelf edge exchange processes in the southern middle Atlantic bight: SEEP-II, tropical studies in Oceanography", *Deep-Sea Res. II*, **41**, 229–703.
- Bishop, J. K. B., J. M. Edmond, D. R. Ketten, M. P. Bacon and W. B. Silker (1977) "The chemistry, biology and vertical flux of particulate matter from the upper 400 m of the equatorial Atlantic Ocean", *Deep-Sea Res.*, **24**, 511–548.
- Blomqvist, S. and C. Kofoed (1981) "Sediment trapping - a subaquatic in-situ experiment", *Limnol. Oceanogr.*, **26**, 585–590.
- Brewer, P. G., Y. Nozaki, D. W. Spencer and A. P. Fleer (1980) "Sediment trap experiments in the deep North Atlantic: isotopic and elemental fluxes", *J. Mar. Res.*, **38**, 703–728.
- Broecker, W. S. and T. H. Peng (1982) *Tracers in the Sea*, Eldigio Press, Palisades, NY, 690 pp.
- Bruland, K. W., R. P. Franks, W. M. Landing and A. P. Fleer (1981) "Southern California inner basin sediment trap calibration", *Earth Planet. Sci. Let.*, **53**: 400–408.
- Buesseler, K. (1991) "Do upper-ocean sediment traps provide an accurate record of particle flux?", *Nature*, **353**, 420–423.
- Butman, C. A. (1986) "Sediment trap biases in turbulent flows: Results from a laboratory flume study", *J. Mar. Res.*, **44**, 645–693.
- Butman, B. and D. W. Fløger (1979) "Long-term observations of bottom current and bottom sediment movement of Mid-Atlantic Continental Shelf", *J. Geophys. Res.*, **84**, 1187–1205.
- Butman, C. A., W. D. Grant and K. D. Stolzenbach (1986) "Predictions of sediment trap biases in turbulent flows: a theoretical analysis based on observations from the literature", *J. Mar. Res.*, **44**, 601–644.
- Calvert, S. (1983) "Sedimentary geochemistry of silicon", in S. R. Aston (ed), *Silicon Geochemistry and Biochemistry*, Academic Press, London, 143–186.
- Cole, J. J., S. Honjo and E. Erez (1987) "Benthic decomposition of organic matter at a deep-water site in the Panama Basin", *Nature*, **327**, 703–704.
- Curry, W. B., R. C. Thunell and S. Honjo (1983) "Seasonal changes in the isotopic composition of planktonic foraminifera collected in Panama Basin sediment traps", *Earth Planet. Sci. Let.*, **64**, 33–43.
- Curry, W. B., D. R. Ostermann, M. V. S. Guptha and V. Ittekkot (1992) "Foraminiferal production and monsoonal upwelling in the Arabian Sea: evidence from sediment traps", in C. P. Summerhayes, W. L. Prell and K. C. Emeis (eds) *Upwelling Systems: Evolution Since the Early Miocene*, Geological Society Special Publication No. 64, 93–106.
- Deuser, W. G. (1986) "Seasonal and interannual variations in deep-water particle fluxes in the Sargasso Sea and their relationship to surface hydrography", *Deep-Sea Res.*, **33**, 225–246.
- Deuser, W. G. and E. H. Ross (1989) "Seasonally abundant planktonic foraminifera of the Sargasso Sea: succession, deep-water fluxes, isotopic compositions, and paleoceanographic implications", *J. Foraminiferal Res.*, **19**, 268–293.

- Deuser, W. G., F. E. Muller-Karger and C. Hemleben (1988) "Temporal variations of particle fluxes in the deep subtropical and tropical North Atlantic: Eulerian versus Lagrangian effects", *J. Geophys. Res.*, **93**, 6857–6862.
- Druffel, E. R. M., S. Honjo, S. Griffin and C. S. Wong (1986) "Radiocarbon in particulate matter from the eastern Sub-Arctic Pacific Ocean: Evidence of a source of terrestrial carbon to the deep sea", *Radiocarbon*, **28**, 397–407.
- Duce, R. A., P. S. Liss, J. T. Merrill, E. L. Atlas, P. Buat-Menard, B. B. Hicks, J. M. Miller, J. M. Prospero, R. Arimoto, T. M. Church, W. Ellis, J. N. Galloway, L. Hansen, T. D. Jickells, A. H. Knap, K. H. Reinhardt, B. Schneider, A. Soudine, J. J. Tokos, S. Tsunogai, R. Wollast and M. Zhou (1991) "The atmospheric input of trace species to the world ocean", *Glob. Biogeochem. Cycles*, **5**, 193–259.
- Dunbar, R. B. and W. N. Berger (1981) "Fecal pellet flux to modern bottom sediments of Santa Barbara Basin (California) based on sediment trapping", *Bull. Geol. Soc. Am.*, **92**, 212–218.
- Dymond, J. (1984) "Sediment traps, particle fluxes, and benthic boundary layer processes", in *Global Ocean Flux Study, Proceedings of a Workshop*, National Academy Press, Washington, D.C., 260–284.
- Dymond, J. and R. Collier (1988) "Biogenic particle fluxes in the equatorial Pacific: Evidence for both high and low productivity during the 1982–1983 El Niño", *Glob. Biogeochem. Cycles*, **2**, 129–137.
- Dymond, J. and M. Lyle (1985) "Flux comparisons between sediments and sediment traps in the eastern tropical Pacific: Implications for atmospheric CO₂ variations during the Pleistocene", *Limnol. Oceanogr.*, **30**, 699–712.
- Dymond, D., P. E. Biscaye and R. W. Rex (1974) "Eolian origin of mica in Hawaiian soils", *Bull. Geol. Soc. Am.*, **85**, 37–40.
- Dymond, J., K. Fisher, M. Clauson, R. Cobler, W. Richardson, M. R. Gardner, W. Berger, A. Soutar and R. Dunbar (1981) "A sediment trap intercomparison study in the Santa Barbara Basin", *Earth Planet. Sci. Lett.*, **53**, 409–481.
- Eppley, R. W. and B. J. Peterson (1979) "Particulate organic matter flux and planktonic new production in the deep ocean", *Nature*, **289**, 677–680.
- Erez, J. and S. Honjo (1981) "Comparison of isotopic composition of planktonic foraminifera in plankton tows, sediment traps and sediments", in W. H. Berger and A. W. H. Bé (eds) *Stable Isotopes and Calcareous Remains in the Ocean, Palaeogeogr., Palaeoclim., Palaeoecol.*, **33**, 129–156.
- Fabry, V. J. (1989) "Aragonite production by pteropod mollusks in the subarctic Pacific", *Deep-Sea Res.*, **36**, 1735–1751.
- Fischer, G., D. Fuetterer, R. Gersonde, S. Honjo, D. R. Ostermann and G. Wefer (1988) "Seasonal variability of particle flux in the Weddell Sea and its relation to ice cover", *Nature*, **335**, 426–428.
- Fowler, S. W., S. Barlestra, J. LaRosa and R. Fukai (1983) "Vertical transport of particulate-associated plutonium and americium in the upper water column of the northeast Pacific", *Deep-Sea Res.*, **30**, 1221–1233.
- Francois, R., S. Honjo, S. J. Manganini and G. Ravizza (1995) "Biogenic barium fluxes to the deep-sea: Implications for paleoproductivity reconstruction", *Glob. Biogeochem. Cycles*, **9**, 289–303.
- Gardner, W. D. (1980a) "Sediment trap dynamics and calibration: A laboratory evaluation", *J. Mar. Res.*, **38**, 17–39.
- Gardner, W. D. (1980b) "Field assessment of sediment traps", *J. Mar. Res.*, **38**, 41–52.
- Gardner, W. D., K. R. Hinga and J. Marra (1983) "Observations on the degradation of biogenic material in the deep ocean with implications on accuracy of sediment trap fluxes", *J. Mar. Res.*, **41**, 195–214.

- Gardner, W. D., J. B. Southard and C. D. Hollister (1985) "Sedimentation, resuspension and chemistry of particles in the northwest Atlantic", *Mar. Geol.*, **65**, 199–242.
- Gowing, M. M. and M. W. Silver (1983) "Origins and microenvironments of bacteria mediating fecal pellet decomposition in the sea", *Mar. Biol.*, **73**, 7–16.
- Gust, G., R. H. Byrne, R. E. Bernstein, P. R. Betzer and W. Bowles (1992) "Particle fluxes and moving fluids: Experience from synchronous trap collections in the Sargasso Sea", *Deep-Sea Res.*, **39**, 1071–1083.
- Haake, B. and V. Ittekkot (1990) "Die Wind-getriebene 'biologische Pumpe' und der Kohlenstoffentzug im Ozean", *Naturwissenschaften*, **77**, 75–79.
- Haake, B., V. Ittekkot, T. Rixen, V. Ramaswamy, R. R. Nair and W. B. Curry (1993) "Seasonality and interannual variability of particle fluxes to the deep Arabian Sea", *Deep-Sea Res. I*, **40**, 1323–1344.
- Handa, N. (1989) "Flux of organic matter at Japan Trench Sites (JT-01 and 02)", *Kaiyo Monthly*, **21**, 197–202.
- Harbison, G. R. and R. Gilmer, R. (1986) "Effects of animal behavior on sediment trap collections: implications for the calculation of aragonite fluxes", *Deep-Sea Res.*, **33**, 1017–1024.
- Hay, B. J., S. Honjo, S. Kempe, V. Ittekkot, E. T. Degens, T. Konuk and E. Izdar (1990) "Interannual variability in particle flux in the southwestern Black Sea", *Deep-Sea Res.*, **37**, 911–928.
- Heath, G. R., T. C. Moore and J. P. Dauphin (1976) "Late Quaternary accumulation rates of opal, quartz, organic carbon, and calcium carbonate in the Cascadia Basin area, northeast Pacific", *Geol. Soc. Am. Memoir*, **145**, 393–409.
- Heiskanen, A.-S. (1990) "Spring bloom dynamics and sedimentation in the coastal northern Baltic Sea", in P. Wassmann, A.-S. Heiskanen and O. Lindahl (eds) *Sediment Trap Studies in the Nordic Countries*, Symposium Proceedings, Kristineberg Marine Biological Station, Sweden, 157–175.
- Hinga, K. R., J. M. Sieburth and G. R. Heath (1979) "The supply and use of organic material by the deep-sea benthos", *J. Mar. Res.*, **37**, 557–579.
- Holligan, P. M., M. Viollier, D. S. Harbour, P. Camus and Campagne-Phillips (1983) "Satellite and ship studies of coccolithophore production along a continental shelf edge" *Nature*, **304**, 339–342.
- Honjo, S. (1975) "Dissolution of suspended coccoliths in the deep-sea water column and sedimentation of coccolith ooze", in W. Sliter, A. W. H. Bé and W. H. Berger (eds) *Cushman Found. Foram. Res. Sp. Publ.*, **13**, 114–128.
- Honjo, S. (1976) "Coccoliths: production, transportation and sedimentation", *Mar. Micropaleont.*, **1**, 65–79.
- Honjo, S. (1977) "Biogenic carbonate particles in the ocean; do they dissolve in the water column", in N. R. Andersen and A. Malahoff (eds) *The Fate of Fossil Fuel CO₂*, Plenum Press, New York, 269–294.
- Honjo, S. (1978) "Sedimentation of materials in the Sargasso Sea at a 5,367 m deep station", *J. Mar. Res.*, **36**, 469–492.
- Honjo, S. (1980) "Material fluxes and modes of sedimentation in the mesopelagic and bathypelagic zones", *J. Mar. Res.*, **38**, 53–97.
- Honjo, S. (1982) "Seasonality of biogenic and lithogenic fluxes in the Panama Basin", *Science*, **218**, 883–884.
- Honjo, S. (1984) "Study of ocean fluxes in time and space by bottom-tethered sediment trap arrays: a recommendation", in *Global Ocean Flux Study, Proceedings of a Workshop*, National Academy Press, Washington, D.C., 305–324.

- Honjo, S. (1990a) "Particle fluxes and modern sedimentation in the polar oceans", in W. O. Smith, Jr. (ed) *Polar Oceanography*, Academic Press, New York, Vol. II, Chapter 13, 322–353.
- Honjo, S. (1990b) "Ocean particle and fluxes of material to the interior of the deep ocean; the azoic theory 120 years later", in V. Ittekkot, S. Kempe, W. Michaelis and A. Spitzky (eds) *Facets of Modern Biogeochemistry*, Springer, Berlin, 62–73.
- Honjo, S. and K. W. Doherty (1988) "Large aperture time-series sediment traps: design objectives, construction and application", *Deep-Sea Res.*, **35**, 133–149.
- Honjo, S. and Manganini, S. J. (1992) "*Biogenic Particle Fluxes at the 34°N 21°W and 48°N 21°W Stations, 1989–1990: Methods and Analytical Data Compilation*", Technical Report of the Woods Hole Oceanographic Institution, WHOI–92–15.
- Honjo, S. and S. J. Manganini (1993) "Annual biogenic particle fluxes to the interior of the North Atlantic Ocean; studied at 34°N 21°W and 48°N 21°W", *Deep-Sea Res. II*, **40**, 587–607.
- Honjo, S. and M. R. Roman (1978) "Marine copepod fecal pellets: Production, transportation and sedimentation", *J. Mar. Res.*, **36**, 45–57.
- Honjo, S., J. F. Connell and P. Sachs (1979) "*Construction of PARFLUX Mark II Sediment Trap; Engineering Report*", Technical Report of Woods Hole Oceanographic Institution, WHOI–79–80, 51 pp.
- Honjo, S., S. J. Manganini and J. J. Cole (1982a) "Sedimentation of biogenic matter in the deep ocean", *Deep-Sea Res.*, **29**, 609–625.
- Honjo, S., S. J. Manganini and L. J. Poppe (1982b) "Sedimentation of lithogenic particles in the open sea" *Mar. Geol.*, **50**, 199–220.
- Honjo, S., S. J. Manganini and G. Wefer (1988) "Annual particle flux and a winter outburst of sedimentation in the northern Norwegian Sea", *Deep-Sea Res.*, **35**, 1223–1234.
- Honjo, S., D. W. Spencer and J. W. Farrington (1982c) "Deep advective transport of lithogenic particles in Panama Basin" *Science*, **216**, 516–518.
- Honjo, S., D. W. Spencer and W. D. Gardner (1992) "A sediment trap intercomparison experiment in the Panama Basin 1979", *Deep-Sea Res.*, **39**, 333–358.
- Honjo, S., K. W. Doherty, Y. C. Agrawal and V. L. Asper (1984) "Direct optical assessment of macroscopic aggregates in the deep ocean", *Deep-Sea Res.*, **31**, 67–76.
- Honjo, S., J. Dymond, R. Collier and S. J. Manganini (1995) "Export production of particles to the interior of equatorial Pacific Ocean during 1992 EqPac experiment", *Deep-Sea Res. II*, **42**, 831–870.
- Hurd, D. C. (1983) "Physical and chemical properties of siliceous skeletons", in S. R. Aston (ed) *Silicon Geochemistry and Biogeochemistry*, Academic Press, London, 187–244.
- IPCC (1990) "*Climate Change: The IPCC Scientific Assessment Report*", prepared for IPCC by Working Group I, J. T. Houghton, G. J. Jenkins and J. J. Ephraim, Cambridge University Press.
- Ittekkot, V. (1991) "Particle flux studies in the Indian Ocean", *EOS*, **72**, 527–530.
- Ittekkot, V. and B. Haake (1990) "The terrestrial link in the removal of organic carbon", in V. Ittekkot, S. Kempe, W. Michaelis and A. Spitzky (eds) *Facets of Modern Biogeochemistry*, Springer, Berlin, 319–325.
- Ittekkot, V., E. T. Degens and S. Honjo (1984a) "Seasonality in the fluxes of sugars, amino acids, and amino sugars to the deep ocean: Panama Basin", *Deep-Sea Res.*, **31**, 1071–1083.
- Ittekkot V., W. G. Deuser and E. T. Degens (1984b) "Seasonality in the fluxes of sugars, amino acids, and amino sugars to the deep ocean: Sargasso Sea", *Deep-Sea Res.*, **31**, 1057–1069.

- Ittekkot, V., B. Haake, M. Bartsch, R. R. Nair and V. Ramaswamy (1992) "Organic carbon removal in the sea: The continental connection", in C. P. Summerhayes, W. L. Prell and K. C. Emeis (eds) *Upwelling Systems: Evolution Since the Early Miocene*, Geological Society Special Publication No. 64, 167–176.
- Ittekkot, V., R. R. Nair, S. Honjo, V. Ramaswamy, M. Bartsch, S. J. Manganini and B. N. Desai (1991) "Enhanced particle fluxes in Bay of Bengal induced by injection of water", *Nature*, **351**, 385–387.
- Jickells, T. D., W. G. Deuser, A. Fleer and C. Hemleben (1990) "Variability of some elemental fluxes in the western tropical Atlantic", *Oceanologica Acta*, **13**, 291–298.
- Jones, P. D., T. M. L. Wigley and S. C. B. Raper (1987) "The rapidity of CO₂-induced climatic change: observations, model results and paleoclimatic implications", in W. H. Berger and L. D. Labeyrie (eds) *Abrupt Climatic Change*, Reidel, Dordrecht, 47–55.
- Karl, D. M. and G. A. Knauer (1989) "Swimmers: A recapitulation of the problem and a potential solution", *Oceanography*, **2**, 25–32.
- Karl, D. M., G. A. Knauer, J. H. Martin and B. B. Ward (1984) "Bacterial chemolithotrophy in the ocean is associated with sinking particles", *Nature*, **309**, 54–56.
- Kellogg, W. W. (1991) "Response to skeptics of global warming", *Bull. Am. Meteorol. Soc.*, **72**, 499–511.
- Kempe, S., H. Nies, V. Ittekkot, E. T. Degens, K. O. Buesseler, H. D. Livingston, S. Honjo, B. J. Hay and S. J. Manganini (1987) "Comparison of Chernobyl nuclide deposition in the Black Sea and in the North Sea", in E. T. Degens, E. Izdar and S. Honjo (eds) *Particle Flux in the Ocean*, Mitt. Geol.-Paläont. Inst. Univ. Hamburg No. 62, 165–178.
- Kitani, K. (1973) "An oceanographic study of the Okhotsk Sea - Particularly in regard to cold waters", *Bull. Far Seas Fish. Res. Lab.*, **9**, 45–76.
- Knauer, G. A., J. H. Martin and K. W. Bruland (1979) "Fluxes of particulate carbon, nitrogen, and phosphorus in the upper water column of the northeast Pacific", *Deep-Sea Res.*, **26**, 97–108.
- Knauer, G. A., D. M. Karl, J. H. Martin and C. N. Hunter (1984) "In-situ effects of selected preservatives on total carbon, nitrogen and metals collected in sediment traps", *J. Mar. Res.*, **42**, 445–462.
- Lampitt, R. S. (1985) "Evidence for the seasonal deposition of detritus to the deep-seafloor and its subsequent resuspension", *Deep-Sea Res.*, **32**, 885–897.
- Lee, C. and C. Cronin (1984) "Particulate amino acids in the sea: Effects of primary production and biological decomposition", *J. Mar. Res.*, **42**, 1075–1097.
- Lee, C., S. G. Wakeham and J. W. Farrington (1983) "Variations in the composition of particulate organic matter in a time-series sediment trap", *Mar. Chem.*, **13**, 181–194.
- Lee, C., S. G. Wakeham and J. I. Hedges (1988) "The measurement of oceanic particle flux - are "swimmers" a problem?", *Oceanography*, **1**, 34–36.
- Lee, C., J. I. Hedges, S. G. Wakeham and N. Shu (1992) "Effectiveness of various treatments in retarding microbial activity in sediment trap material and their effects on the collection of swimmers", *Limnol. Oceanogr.*, **37**, 117–130.
- Lerman, A. (1979) *Geochemical Processes, Water and Sediment Environments*, John Wiley & Sons, New York, 48 pp.
- Lisitzin, A. P. (1972) *Sedimentation in the World Ocean*, Society of Economic Paleontologists and Mineralogists, Special Publication No. 17, 218 pp.
- Manganini, S. J., S. Honjo, M. Altabet and M. Honda (1994) "The effects of preservatives on settling particles as collected by sediment traps during the EqPac experiment", *Am. Geophys. Union, Am. Soc. Limnol. Oceanogr.*, **75** (3), 84 (Abstract).
- Martin, J. H., G. A. Knauer, D. M. Karl and W. W. Broenkow (1987) "VERTEX: Carbon cycling in the northeast Pacific", *Deep-Sea Res.*, **34**, 267–285.

- Masuzawa, T., S. Noriki, T. Kurosaki, S. Tsunogai and M. Koyama (1989) "Compositional change of settling particles with water depth in the Japan Sea", *Mar. Chem.*, **27**, 61–78.
- Matsuoka, K. (1989) "Palynomorphs in the sediment trap materials collected from Japan Trench (JT-01 and 02)", *Kaiyo Monthly*, **21**, 232–268.
- Meinecke, G. and G. Wefer (1990) "Seasonal pteropod sedimentation in the Norwegian Sea", *Palaeogeogr., Palaeoclim., Palaeoecol.*, **79**, 127–147.
- Michaelis, W., P. Schumann, V. Ittekkot and T. Konuk (1987) "Sterol markers for organic matter fluxes in the Black Sea", in E. T. Degens, E. Izdar and S. Honjo (eds) *Particle Flux in the Ocean*, Mitt. Geol.-Paläont. Inst. Univ. Hamburg No. 62, 89–98.
- Michaels, A. F., M. W. Silver, M. M. Gowing and G. A. Knauer (1990) "Cryptic zooplankton "swimmers" in upper ocean sediment traps", *Deep-Sea Res.*, **37**, 1285–1296.
- Milliman, J. D. (1974) *Marine Carbonates*, Springer-Verlag, New York, 375 pp.
- Milliman, J. D. (1993) "Production and accumulation of calcium carbonate in the ocean: budget of a long-term steady state?", *Glob. Biogeochem. Cycles*, **7**, 927–957.
- Mills, E. L. (1983) "Problems of deep-sea biology: An historical perspective", in T. T. Row (ed) *Deep-Sea Biology, 8. The Sea*, John Wiley & Sons, New York, 1–76.
- Mopper, K. and E. T. Degens (1972) "*Aspects of the biogeochemistry of carbohydrates and proteins in aquatic environments*", Woods Hole Oceanographic Institution Technical Report, WHOI-72-68, 188 pp.
- Murray, J. W., R. T. Barber, M. R. Roman, M. P. Bacon and R. A. Feely (1994) "Physical and biological controls on carbon cycling in the equatorial Pacific", *Science*, **226**, 58–65.
- Nair, R. R., V. Ittekkot, S. J. Manganini, V. Ramaswamy, B. Haake, E. T. Degens, B. N. Desai and S. Honjo (1989) "Increased particle flux to the deep ocean related to monsoons", *Nature*, **338**, 749–751.
- Nelson, D. M. and J. J. Goering (1977) "Near-surface silica dissolution in the upwelling region off northwest Africa", *Deep-Sea Res.*, **24**, 31–36.
- Newton, P. P., R. S. Lampitt, T. D. Jickells, P. King and C. Boutle (1994) "Temporal and spatial variability of biogenic particle fluxes during the JGOFS northeast Atlantic process studies at 47°N, 20°W", *Deep-Sea Res.*, **41**, 1617–1642.
- Narita, H., K. Harada and S. Tsunogai (1990) "Lateral transport of sediment particles in Okinawa Trough determined by natural radionuclides", *Geochem. J.*, **24**, 207–216.
- Noriki, S. and S. Tsunogai (1986) "Particle fluxes and major components of settling particles from sediment trap experiments in the Pacific Ocean", *Deep-Sea Res.*, **33**, 903–912.
- Nozaki, Y. (1986) "Ocean-scavenging model", *Geochemistry (in Japanese)*, **20**, 69–77.
- Nozaki, Y. (1989a) "On the environmental study of trench", *Kaiyo Monthly*, **21**, 187–191.
- Nozaki, Y. (1989b) "Radionuclide fluxes obtained by a super-deep sediment trap experiment", *Kaiyo Monthly*, **21**, 192–196.
- Nozaki, Y., H. S. Yang and M. Yamada (1987) "Scavenging of thorium in the ocean", *J. Geophys. Res.*, **92**, 772–778.
- Okada, H. and S. Honjo (1973) "The distribution of oceanic coccolithophorids in the Pacific", *Deep-Sea Res.* **20**, 355–374.
- Osterberg, C., A. G. Carey, and H. Curl (1963) "Acceleration of sinking rates of radionuclides in the sea", *Nature*, **200**, 1276–1277.
- Pace, M. L., G. A. Knauer, D. M. Karl and J. M. Martin (1987) "Primary production, new production and vertical flux in the eastern Pacific ocean", *Nature*, **325**, 803–804.
- Paffhofer, G. A. and S. C. Knowles (1979) "Ecological implications of fecal pellet size, production and consumption by copepods", *J. Mar. Res.*, **37**, 35–49.

- Peinert, R., B. von Bodungen and V. S. Smetacek (1989) "Food web structure and loss rate" in W. H. Berger, V. S. Smetacek and G. Wefer (eds) *Productivity of the Ocean: Present and Past*, John Wiley & Sons, Chichester, 35–48.
- Peinert, R., U. Bathmann, B. von Bodungen and T. Noji (1987) "The impact of grazing on spring phytoplankton growth and sedimentation in the Norwegian Current", in E. T. Degens, E. Izdar and S. Honjo (eds) *Particle Flux in the Ocean*, Mitt. Geol.-Paläont. Inst. Univ. Hamburg No. 62, 149–164.
- Peterson, M. L., P. J. Hernes, D. S. Thoreson, J. I. Hedges, C. Lee and S. G. Wakeham (1993) "Field evaluation of a valved sediment trap", *Limnol. Oceanogr.*, **38**, 1741–1761.
- Pfannkuche, O. and K. Lochte (1993) "Open ocean pelago-benthic coupling: Cyanobacteria as tracers of sedimenting salp faeces", *Deep-Sea Res.*, **40**, 727–737.
- Pilskaln, C. H. and S. Honjo (1987) "The fecal pellet fraction of biogeochemical particle fluxes to the deep sea", *Glob. Biogeochem. Cycles*, **1**, 31–48.
- Ramaswamy, V., R. R. Nair, S. J. Manganini, B. Haake and V. Ittekkot (1991) "Lithogenic fluxes to the deep Arabian Sea measured by sediment traps", *Deep-Sea Res.*, **38**, 169–184.
- Rex, R. W. and E. D. Goldberg (1958) "Quartz contents of pelagic sediments of the Pacific Ocean", *Tellus*, **10**, 153–159.
- Robb, D. (1984) "Stereo-biochemistry and function of polymers in microbial adhesion and aggregation", in K. C. Marshall (ed) *Microbial Adhesion and Aggregation*, Springer-Verlag, Berlin, 39–49.
- Romankevich, E. A. (1984) *Geochemistry of Organic Matter in the Ocean*, Springer-Verlag, Berlin. 334 pp.
- Schrader, H. J. (1971) "Fecal pellets in sedimentation of pelagic diatoms", *Science*, **174**, 55–57.
- Shanks, A. L. and J. D. Trent (1980) "Marine snow: Sinking rates and potential role in vertical flux", *Deep-Sea Res.*, **27**, 137–144.
- Siegel, D. A., T. C. Granata, A. F. Michaels and T. D. Dickey (1990) "Mesoscale eddy diffusion, particle sinking, and the interpretation of sediment trap data", *J. Geophys. Res.*, **95**, 5305–5311.
- Silver, M. W. and A. L. Alldredge (1981) "Bathypelagic marine snow: Deep-sea algal and detrital community", *J. Mar. Res.*, **39**, 501–530.
- Silver, M. W. and K. W. Bruland (1981) "Differential feeding and fecal pellet composition of slaps and pteropods, and the possible origin of deep water flora and olive green "cells"", *Mar. Biol.*, **62**, 263–273.
- Small, L. F., S. W. Fowler and M. Y. Ünlü, M. Y. (1979) "Sink rates of natural copepod fecal pellets", *Mar. Biol.*, **51**, 233–241.
- Smayda, T. J. (1970) "Normal and accelerated sinking of phytoplankton in the sea", *Oceanogr. Mar. Biol.*, **8**, 353–414.
- Smetacek, V. S. (1985) "The role of sinking in diatom life-history cycles: ecological, evolutionary and geological significance", *Mar. Biol.*, **84**, 239–251.
- Spencer, C. P. (1983) "Marine biogeochemistry of silicon", in S. R. Aston (ed), *Silicon Geochemistry and Biochemistry*, Academic Press, London, 101–141.
- Spencer, D. W., P. G. Brewer, A. Fleer, S. Honjo, S. Krishnaswami and Y. Nozaki (1978) "Chemical fluxes from a sediment trap experiment in the deep Sargasso Sea", *J. Mar. Res.*, **36**, 493–523.
- Steinmetz (1991) "Calcareous nannoplankton biocoenosis: sediment trap studies in the equatorial Atlantic, central Pacific, and Panama Basin", in S. Honjo (ed) *Ocean Biocoenosis*, Series No. 1, Woods Hole Oceanographic Institution Press, Woods Hole, Mass., 1–85.

- Suess, E. (1980) "Particulate organic carbon flux in the ocean-surface productivity and oxygen utilization", *Nature*, **288**, 260–263.
- Suzuki, N. and K. Kato (1953) "Studies on suspended materials. Marine snow in the sea, part 1, Source of marine snow", *Bulletin of the Faculty of Fisheries, Hokkaido University*, **4**, 132–135.
- Takahashi, K. (1983) "Radiolaria: sinking population, standing stock and production rate", *Marine Micropaleontology*, **7**, 441–447.
- Takahashi, K. (1986) "Seasonal fluxes of pelagic diatoms in the subarctic Pacific 1982–1983", *Deep-Sea Res.*, **33**, 1225–1251.
- Takahashi, K. (1989) "Silicoflagellates as productive indicators: evidence from long temporal and spatial flux variability responding to hydrography in the northeastern Pacific", *Glob. Biogeochem. Cycles*, **3**, 43–61.
- Takahashi, K. (1991) "Radiolaria: Flux, Ecology, and Taxonomy in the Pacific and Atlantic", in S. Honjo (ed) *Ocean Biocoenosis*, Series No. 3, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA, 303 pp.
- Takahashi, K. (1994) "Coccolithophorid biocoenosis production and flux in the deep sea", in J. C. Green and B. S. C. Leadbeater (eds) *Systematics Association Special Volume 51*, Clarendon Press, Oxford, 335–350.
- Takahashi, K. and A. W. H. Bé (1984) "Planktonic foraminifera: factors controlling sinking speeds", *Deep-Sea Res.*, **31**, 1477–1500.
- Takahashi, K. and S. Honjo (1981) "Vertical flux of Radiolaria: A taxon-quantitative sediment trap study from the western Tropical Atlantic", *Micropaleontology*, **27**, 140–190.
- Takahashi, K. and S. Honjo (1983) "Radiolarian skeletons: size, weight, sinking speed, and residence time in tropical pelagic oceans", *Deep-Sea Res.*, **30**, 543–568.
- Takahashi, K., D. C. Hurd and S. Honjo (1983) "Phaeodarian skeletons: their role in silica transport to the deep sea", *Science*, **222**, 616–618.
- Takahashi, T. (1975) "Carbonate chemistry of sea water and the calcite compensation depth in the oceans", in W. V. Sliter, A. H. Bé and W. H. Berger (eds) *Dissolution of Deep-Sea Carbonates*, Cushman Foundation Foraminiferal Res. Sp. Pub. 13, 11–26.
- Takahashi, T., C. Goyet, D. Chipman, E. Peltzer, J. Godard and P. G. Brewer (1990) "Ratio of the organic carbon and calcium carbonate productions observed at JGOFS 47°N 20°W site", (abstract). JGOFS North Atlantic Bloom Study Symposium, 1990, Washington, D. C.
- Tanoué, E. and N. Handa (1986) "Origin of sugars and amino-sugars in marine sediments", *Oceanogr. Acta*, **10**, 91–99.
- Thunell, R. C. and S. Honjo (1987) "Foraminiferal fluxes as an indicator of productivity variability at Ocean Station P, Gulf of Alaska", *Nature*, **326**, 216–218.
- Thunell, R., C. Pride, E. Tappa and F. Muller-Karger (1993) "Varve formation in the Gulf of California: insights from time series sediment trap sampling and remote sensing", *Quaternary Science Review*, **12**, 451–464.
- Thunell, R. C., C. H. Pilskaln, E. Tappa and L. Reynolds-Sauter (1994a) "Temporal variability in sediment fluxes in the San Pedro Basin, Southern California Bight", *Continental Shelf Res.*, **14**, 333–352.
- Thunell, R. C., W. S. Moore, J. Dymond and C. H. Pilskaln (1994b) "Elemental and isotopic fluxes in the Southern California Bight: A time-series sediment trap study in the San Pedro Basin", *J. Geophys. Res.*, **99**, 875–889.
- Traverse, A. (1988) *Paleopalynology*, Unwin Hyman, Boston, xxiii + 600 pp.
- Tsujita, T. (1953a) "A preliminary study on naturally occurring suspended organic matter", *Records of Oceanographic Works in Japan*, **2**, 94–100.

- Tsujita, T. (1953b) "Studies on naturally occurring suspended organic matter in waters adjacent to Japan. On an application of the suspended organic matter for the analysis of water masses", *Records of Oceanographic Works in Japan*, **2**, 113–126.
- Tsunogai, S. (1987) "'Train-passenger model' as an oceanic removal mechanism of chemical elements in seawater", *Geochemistry*, **21**, 75–82 (in Japanese).
- Tsunogai, S. and T. Kondo (1987) "Sporadic transport and deposition of continental aerosols to the Pacific Ocean", *J. Geophys. Res.*, **87**, 8870–8874.
- Tsunogai, S. and S. Noriki (1991) "Particulate fluxes of carbonate and organic carbon in the ocean. Is the marine biological activity working as a sink of the atmospheric carbon?", *Tellus*, **43B**, 256–266.
- Tsunogai, S., S. Noriki, K. Harada and K. Tate (1990) "Vertical change index for the particulate transport of chemical and isotopic components in the ocean", *Geochem. J.*, **24**, 229–244.
- Tsunogai, S., S. Noriki, K. Harada, T. Kurosaki, Y. Watanabe and M. Maeda (1986) "Large but variable particulate flux in the Antarctic Ocean and its significance for chemistry of Antarctic water", *Journal of the Oceanographical Society of Japan*, **42**, 83–90.
- Tuji, S. (1993) "Time-lapse observation of marine snow in Sagami Bay using new optics", (abstract). Biogeochemical Cycles in the Ocean. JAMSTEC workshop, Yokosuka, Dec. 1993.
- Turner, J. T. and J. A. Ferrante (1979) "Zooplankton fecal pellets in aquatic ecosystems", *BioScience*, **29**, 670–677.
- von Bodungen, B., G. Fischer, E.-M. Nöthig and G. Wefer (1987) "Sedimentation of krill faeces during spring development of phytoplankton in Bransfield Strait, Antarctica", in E. T. Degens, E. Izdar and S. Honjo (eds) *Particle Flux in the Ocean*, Mitt. Geol.-Paläont. Inst. Univ. Hamburg No. 62, 243–257.
- Wakeham, S. G. and E. A. Canuel (1986) "Lipid composition of the pelagic crab *Pleuroncodes planipes*, its feces, and sinking particulate organic matter in the equatorial North Pacific Ocean", *Org. Geochem.*, **9**, 331–343.
- Wakeham, S. G., J. W. Farrington, R. B. Gagosian, C. Lee, H. de Baar, G. E. Nigrelli, W. Tripp, S. O. Smith and N. M. Frew (1980) "Organic matter fluxes from sediment traps in the equatorial Atlantic Ocean", *Nature*, **286**, 798–799.
- Walsh, J. J. (1988) *On the Nature of Continental Shelves*, Academic Press, San Diego, 520 pp.
- Walsh, J. J. (1994) "Particle export at Cape Hatteras", *Deep-Sea Res.*, **41**, 603–628.
- Walsh, J. J., G. T. Rowe, R. L. Iverson and C. P. McRoy (1981) "Biological export of shelf carbon: a neglected sink of the global CO₂ cycle", *Nature*, **291**, 196–201.
- Wassmann, P. and D. Slagstad (1990) "Mathematical modeling, an important tool to explore the dynamics of vertical flux of organic matter", in P. Wassmann, A.-S. Heiskanen and O. Lindahl (eds) *Sediment Trap Studies in the Nordic Countries*, Symposium Proceedings, 2, Kristineberg Marine Biological Station, Sweden, 255–279.
- Wefer, G. (1989) "Particle flux in the ocean: effects of episodic production", in W. H. Berger, V. S. Smetacek and G. Wefer (eds), *Productivity of the Ocean, Present and Past*, John Wiley & Sons, Chichester, 139–153.
- Wefer, G. (1991) "Stofftransport zum Meeresboden: Eine Übersicht", *Naturwissenschaften*, **78**, 1–6.
- Wefer, G., G. Fischer, D. Fütterer and R. Gersonde (1988) "Seasonal particle flux in the Bransfield Strait (Antarctica)", *Deep-Sea Res.*, **35**, 891–898.