

By far the largest airborne transportation of lithogenic matter is Kosa (which means "yellow sand") from Eurasian Drylands, including the Gobi Desert (Tsunogai and Kondo, 1987). Kosa is transported eastward by the high-altitude jet stream and travels to the eastern North Pacific; it covers wide areas of the western and central Pacific seafloor (e.g., Rex and Goldberg, 1958). As a proof of this long-distance transport, mica particles of granitic origin in Kosa, older than Hawaii, have been found in the soil of that mid-ocean basalt island (Dymond et al., 1974).

The second area that supplies lithogenic particles is the central African desert. The trade winds carry dust plumes westward across the North Atlantic. Large plumes in the spring occasionally travel as far as the Florida peninsula, and the dust from Africa is found in the snow fields of the high Andes (this volume, Chapter 3). The third area of open ocean which receives a significant amount of lithogenic aerosol is the Arabian Sea. Desert dust is transported from coastal drylands along the west coast of the Arabian Sea as well as from far-distant interior North Africa. In the Arabian Sea, lithogenic particle fluxes were as large as about 4 to $9 \text{ g m}^{-2} \text{ y}^{-1}$ (Ramaswamy et al., 1991; Haake et al., 1993).

7.6 PARTICLE REMOVAL PROCESSES

7.6.1 REMOVAL PROCESSES OF PRIMARY PRODUCTION BY PARTICLES

At the $48^{\circ}\text{N } 21^{\circ}\text{W}$ JGOFS station, dissolved inorganic nutrients decreased rapidly during April 1989, as the phytoplankton bloom in the euphotic layer progressed. Between 8 and 18 of May, dissolved SiO_3 , NO_3 and PO_4 were virtually depleted from the upper 50 m. After this period, these nutrients slowly recovered in the surface layer. In the same area, during the period from May 29 to June 13, the particle flux, caught in a sediment trap set in the 2-km-deep layer, suddenly increased (Figure 7.6). This scenario is explained as phytoplankton photosynthesis converting all available inorganic nutrients in the euphotic layer to particulate matter, some arriving in the ocean's interior within a short time, supporting the view of rapid transportation to the ocean's interior.

7.6.2 "LEAKY" BELT CONVEYOR

Only a part of the nutrients converted to organic particulate matter actually did arrive in the ocean's interior during the above-mentioned experiment; about 30% of SiO_3 and as little as 1.7% of NO_3 which had been removed from the surface layer was delivered to the 2-km trap; only 1.3% of organic matter was produced

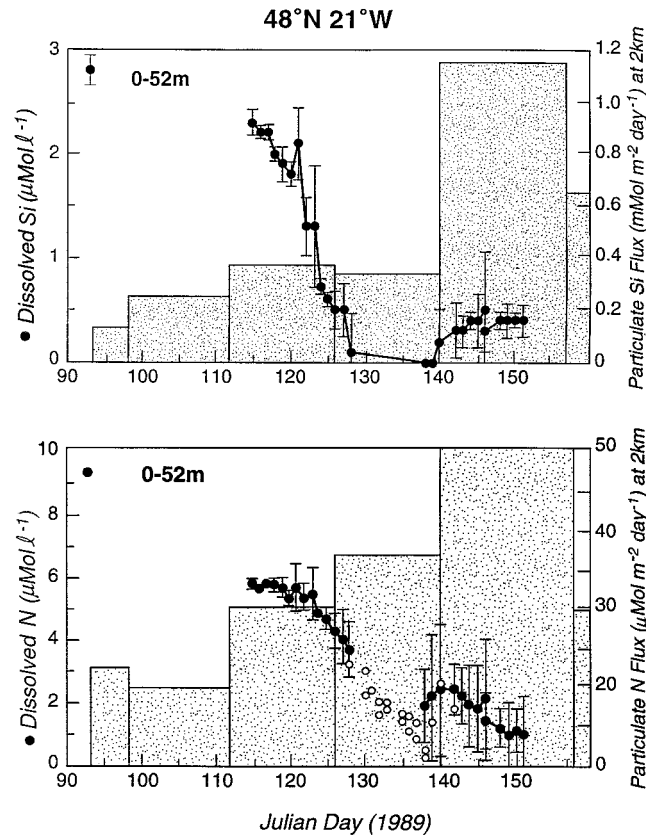


Figure 7.6 Variability of dissolved SiO_3 (upper panel) and NO_3 (lower panel) in the upper surface layer (0–52 m) from April 3 to May 31, 1989 at $48^\circ\text{N } 21^\circ\text{W}$ compared with biogenic SiO_2 and particulate N fluxes at the same station (right axis) (Honjo and Manganini, 1993).

by photosynthesis (Honjo and Manganini, 1993). The organic matter in the living cell, in cytoplasm as liquid, can be returned to the DOM pool immediately. The nutrients and organic carbon which did not arrive at 2 km thus were recycled back to the water column before they reached that point. Therefore, a significant portion of nutrients were recycled where the organisms lived. Settling particles, both amorphous aggregates and fecal pellets, attract microbial activity (Turner and Ferrante, 1979; Karl et al., 1984; Alldredge and Hartwig, 1986); thus the mineralization of organic constituents is accelerated, and they also return to the dissolved pool. The protective membranes of fresh fecal pellets of metazoans usually disappear by degradation before they settle through the euphotic layer and

allow exchange of interstitial liquids with seawater (Honjo and Roman, 1978). These observations, as well as the fact that fine particles continue to slough off from the host settling particles, suggest that the transportation mechanism of particles, or the removal process of organic matter from the euphotic layer to the ocean's interior, can be described as a "leaky" belt conveyor.

7.6.3 NEED FOR BALLAST

The physical parameters of aggregates which arrive in the ocean's interior are not well known. As previously explained, an aggregate is highly porous ($> 99\%$; Alldredge and Gotschalk, 1988), encapsulated by a viscous watery layer which further reduces net gravity. The main framework of an amorphous aggregate is made of material of about equal density with water, such as cellulose (dry weight = 1.5 g cm^{-3}) and other biopolymers. The density of living plankton has been reported as 1.025 g cm^{-3} (Smayda, 1970) which is about the same as the density of water. Because of the large water and organic content (Calvert, 1983), the in-water density of biogenic SiO_2 of many diatom frustules and radiolarian shells is not much different from water (Takahashi et al., 1983; Takahashi, 1991). Although shallow-ocean aggregates are different from the ones settling to the deep ocean, Alldredge and Gotschalk (1988) observed that the median absolute density of the aggregates of marine snow collected from the San Pedro Basin (neretic) was $1.02502 \text{ g cm}^{-3}$.

It is obvious that an aggregate could not settle vertically through the water column without ballast (e.g., Ittekkot and Haake, 1990). CaCO_3 is the densest of marine components ($d_{\text{air}} = 2.71$). Quartz or volcanic glass follow. Coccoliths, juvenile planktonic foraminifera and small pteropod shells (aragonite is slightly denser than calcite) can be used also as efficient ballast to settle aggregates. As previously mentioned, carbonate is usually the most abundant component in settling particles compared to other particle classes in the world's oceans (except for the Antarctic Ocean; Fischer et al., 1988; Wefer et al., 1988). Forty to 60% of the total mass consists of CaCO_3 particles. The descending speed of particles is generally faster during the bloom period when coccoliths are abundantly produced in the upper ocean (e.g., Honjo and Manganini, 1993). This can also be observed in the equatorial Pacific where the carbonate content in settling particles is significantly larger (up to 65% of total dry mass) than at other stations (Honjo et al., 1995).

Aerosol particles also serve as ballast to remove settling particles from surface layers. In the Arabian Sea, the variability of particle fluxes in the ocean's interior was more positively correlated with wind speed than with surface temperature, which indicates upwelling (Nair et al., 1989; this volume, Chapter 14). This perhaps can be related to the deposition of airborne clay and framework silicate particles which were incorporated into ordinary settling particles enhancing their

settling speeds during productive monsoon periods (Ittekkot and Haake, 1990; Ittekkot, 1991). Ittekkot et al. (1991) also argued that the enhanced particle flux in the Bay of Bengal was attributed to fresh water which contains denser, suspended lithogenic particles derived during the monsoon from the continent (this volume, Chapter 15). Jickells et al. (1990) found that the organic carbon and Al flux is positively correlated in the samples from the Sargasso Sea.

7.6.4 SETTLING PARTICLES VS. SUSPENDED PARTICLES

Because of large differences in the velocity between settling particles (such as marine snow and fecal pellets) and independently suspended fine particles, the former should continue gathering the latter on their "sticky" surfaces while descending.

Meantime water shear forces tear off detritus from the surface of settling particles, as previously explained. Such particles, resuspended while descending, are recaptured, sooner or later, by other, passing settling particles. This cycle would be repeated throughout the water column. This model implies that particles which are suspended in deep layers are not necessarily older than ones in shallow layers, and vice versa.

A mixture of fresh and more corroded fragments of coccoliths were found suspended in the highly under-saturated layers of the Pacific (Honjo, 1975). This is one piece of evidence which supports the above "bus-rider"-hypothesis explanation of the "Coccolith Riddle" of the 1970's (Honjo, 1976). When a coccolith remains in suspension for relatively long periods, without being recaptured by other settling particles, it progressively loses its volume which further slows the descent speed, or it disappears by disintegration and dissolution. Although their quantity is still unknown, such coccoliths which dissolve *in situ* contribute to increased deep-water alkalinity. In the under-saturated deep layers of the North Pacific, the number of suspended coccoliths rapidly decreases with depth (Okada and Honjo, 1973) (Figure 7.7), supporting the above explanation, but the flux of carbonate is maintained throughout the abyssal layers (Honjo et al., 1995). This implies that the net dissolution of carbonate caused by sloughed-off coccoliths is not significant, but that coccoliths are recaptured by passing-by settling particles, causing the majority to arrive in the deep interior. The rate of exchange between suspended and settling coccoliths can be constrained mainly by: 1) the residence time of suspended coccoliths in the under-saturated water column; 2) the population of suspended coccoliths; and 3) the descending speed of settling particles. The rate of scavenging and departure of fine, independent particles to/from settling particles in the ocean's interior was better constrained by using radionuclei decay factors (Nozaki, 1986; Nozaki et al., 1987) and further developed by Tsunogai (1987) as the "train-passengers model".

Another riddle: Which are the originals, suspended or settling particles? In fact, they are inseparable and their relationship is dynamic. The majority of ocean particles produced in the upper layers are in suspended-particle size. Without settling particles, there will be no suspended particles in the ocean's interior.

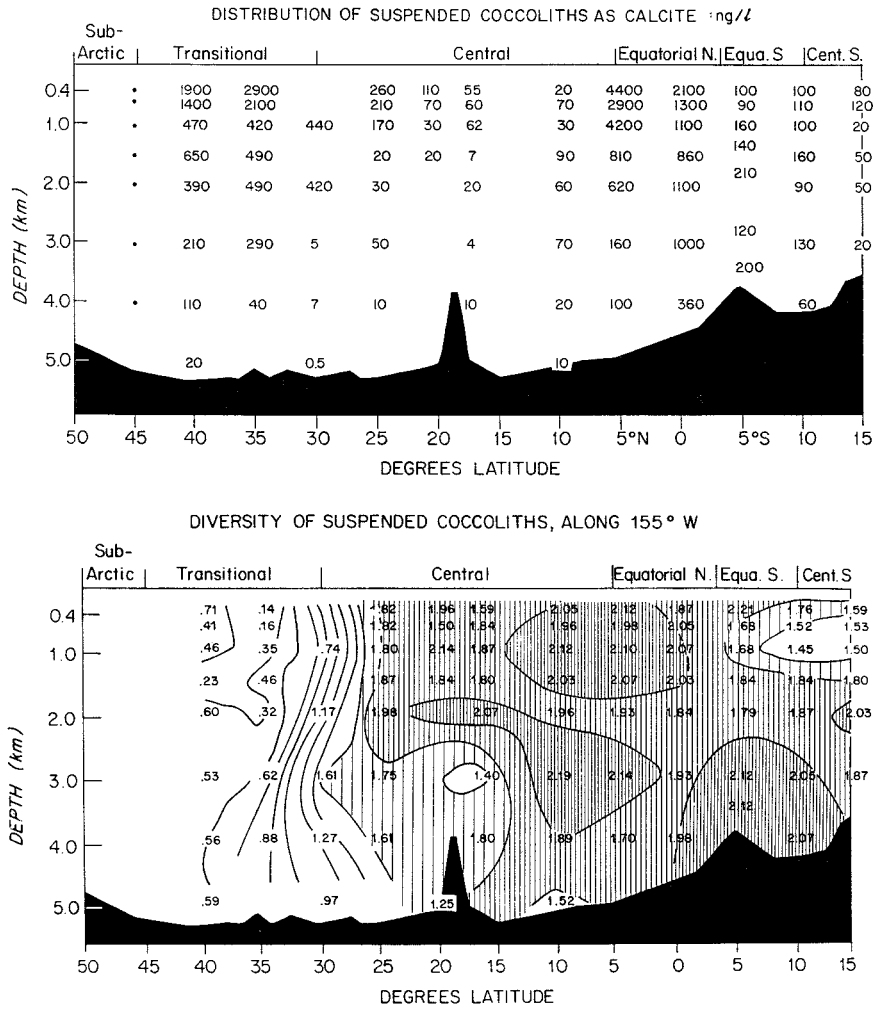


Figure 7.7 The distribution of the estimated total weight of the suspended coccoliths in ng per liter of sea water from 50°N to 15°S along 155°W (upper panel). Note that the weight decreases rapidly with depth at the transitional, central and northern equatorial zone stations. Suspended coccoliths did not decrease as much as at the other stations at the Equator and central zones in the southern hemisphere. On the other hand, the Shannon Weaver's species diversity of suspended coccoliths does not change significantly with depth (lower panel) (Honjo, 1975).

7.7 SETTLING RATES OF PARTICLES

7.7.1 ESTIMATION OF THE RESIDENCE TIME OF PARTICLES FROM OFF-SETTING BENCHMARKS

The "temporal off-set" of "benchmarks" of fluxes have been repeatedly found by a number of open-ocean, synchronized, time-series sediment trap experiments (e.g., Honjo, 1984). "Benchmarks" are defined as traceable time events such as peaks or valleys of total mass or component fluxes, normal and unusual blooms (Honjo and Manganini, 1993), blooms of specific taxonomic units (Takahashi, 1986), and meteorological forcing events such as onset of the monsoon and high-wind events (Ittekkot and Haake, 1990; Nair et al., 1989; Hay et al., 1990; Ramaswamy et al., 1991).

Off-set of benchmarks constrains the residence time of mass or bulk particles between the depths where two or more time-series traps are deployed in a depth series. The open/close timing of all sediment traps involved in an experiment must be synchronized. A flux "peak", one of the most useful benchmarks, is caused by the upper ocean layer producing and supplying a higher density of settling particles such as marine snow and/or settling particles with a higher sinking speed as a pulse. A flux "valley" is generated by a condition in reverse of the peak.

To estimate the average residence time of settling particles (R_{ave}) by offset of arrival of a benchmark, the temporal resolution (and the range of error) is the same as a trap open period. In case benchmarks occur at the same time, the settling particles reside between two traps for a shorter time than one open period (t). When a benchmark arrives at the deeper trap one open period (t) later, R_{ave} equals t . The maximum residence time of individual particles is $2t$, and the minimum is 0. When a benchmark skips one period at the deep trap, R_{ave} is $2t$, the maximum residence time of individual particles is $3t$ and the minimum is t . The shorter the open period (t), the higher the resolution of residence time to be estimated. However, on a practical basis, an open/close schedule cannot be set too short for resolving the finer arrival sequence of benchmarks. Particles collected by a funnel-shaped trap adhere to the interior wall of the cone, then slide down the slope making frequent micro-avalanches before settling in the sample bottles located at the bottom of the trap. This perturbs the chronological relationship between arriving particles. For a commonly used trap with a 0.5 m^2 aperture, this period of perturbation lasts an average of several days (Honjo and Manganini, unpublished data).

7.7.2 SETTLING SPEED OF PARTICLES

The bulk descending speed of settling particles for an open period can be obtained by dividing the depth between a pair of traps (D_p) by R_{ave} . As an example of D_p/R_{ave} estimate, Ocean Station P in the Gulf of Alaska (Honjo, 1984) can be cited. The highest flux peak observed at the 1-km trap appeared one period ($t = 15$ days) later in the 3.8-km trap moored at the same location ($D_p = 2.8$ km). The average bulk settling velocity was thus estimated as 200 m d^{-1} with the minimum speed of 93 m d^{-1} . We also found that this average settling velocity was applicable to all three basic particle classes including organic carbon (Figure 7.8) (database by Dr. C. S. Wong, the Institute of Ocean Sciences, Sydney, BC, Canada). The peak maximum of biogenic particle flux observed at this station was as large as $600 \text{ mg m}^{-2} \text{ d}^{-1}$ in late July 1983. The average bulk settling velocity during this high-flux period was faster than during a period of normal flux.

As another example of such estimation, at $48^\circ\text{N } 21^\circ\text{W}$, a JGOFS North Atlantic Bloom Experiment (NABE) station, we deployed 3 traps at approximately 1, 2 and 3.7 km along a mooring (Figure 7.9). The bloom in the spring of 1989 observed at 1 km was repeated at 2 and 3.7 km. The two peaks observed at 2 km (the middle day of the open period: JD 148 = May 29, 1989 and JD 178 = June 27, 1989) were fused into a single broad peak on JD 164 (= June 13, 1989) seemingly retarding the first peak (JD 148). Curiously, the peak on JD 148 at 1 km was smaller than that at 2 km, and the prominent peak on JD 178 was not found at 1 km (Figure 7.9). Eddy movement may be an explanation (Newton, et al., 1994). This "missing flux" has also occurred at a number of other locations (Honjo and Manganini, 1993).

Although the flux at 2 km decreased abruptly after the JD 192 period, the flux at 3.7 km decreased gradually to the end of the post-bloom period, suggesting that the sedimentation ended at 2 km but continued at 3.7 km during this period. The percentage of biogenic SiO_2 increased in the sediment caught at the 3.7-km trap due to the increased content of diatom frustules. We speculate that light frustules with large surface areas took more time to settle through the water column (Honjo and Manganini, 1993). The maximum fluxes of *Bacteriastrum delicatum* at 1 and 2 km, an abundant chain-form diatom, were observed during the periods which occurred on May 13 and June 13, respectively, taking about a month to settle through only one kilometer. The maximum flux of this diatom species at 3 km occurred during the period on June 27, only two weeks later, even though covering more distance, 1.7 km. Such apparent acceleration of sedimentation at deep layers at this station was observed in a number of other diatom species and silicoflagellate species.

The sequential pattern of the total flux during the 1990 bloom period at $34^\circ\text{N } 21^\circ\text{W}$ at the 1248-m trap was generally repeated at deeper traps, particularly in the first month, indicating that the onset of surface bloom rapidly propagated to the ocean's interior within one open/close time period (Figure 7.9). At the middle

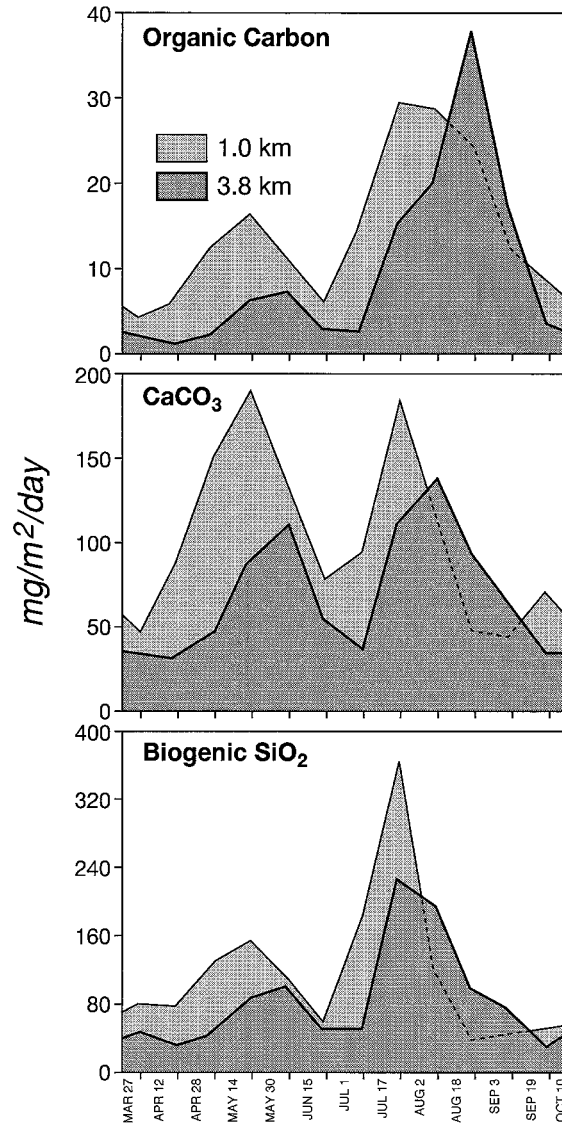


Figure 7.8 Organic carbon, CaCO_3 and biogenic SiO_2 flux at Ocean Station P, 50°N 145°W from March to October, 1983. The bench marks of flux delays for one open period (15 days). A significant peak of organic carbon during the period August 15 to September 3 at 3.8 km which was dominated by gelatinous zooplankton remains, was not observed at 1.0 km depth. This may indicate an eddy effect (Honjo, 1985).

trap, only 628 m deeper than the shallowest, at 1248 m, two peaks fused into one peak. Although the amplitude of flux variability during each period was reduced in the deepest (4371-m) trap, the benchmarks of the middle trap, which was 2.5 km above, arrived during the same period. This observation suggests that, at this station, the settling speed of bulk particles during the bloom episode was more rapid in the deeper than in the shallower part of the water column.

The observations explained above indicate that the descending speed of particles appears to fall in a relatively narrow range; the average ranges from 80 m d^{-1} to 200 m d^{-1} . This is in the range of the descending speed of fecal pellets produced by common grazing mesozoans as determined under laboratory conditions (Smayda, 1966; Small et al., 1979). However, some classes of ocean particles are de-coupled from this normal settling particle sedimentation scheme and show much faster settling velocities. For example, although not yet confirmed in the field, Fowler and Small (1972) reported, from a laboratory experiment, a much faster (several thousand meters a day) sinking speed of euphausiid's fecal pellets. At $48^\circ\text{N } 21^\circ\text{W}$, adult-stage planktonic foraminifera tests ($> 150 \mu\text{m}$) were caught in the same period at all depths from 1 km to 3.4 km, indicating that they settle independently at their own Stokesian sinking speed (Berger and Piper, 1972; Takahashi and Bé, 1984) penetrating the layer of more slowly settling marine snow (Figure 7.10). This suggests near instant copying of the environment where the foraminifera are grown on the deep ocean floor. If this mode of plankton growth is common in the other oceans, this fact would strengthen the proximity of

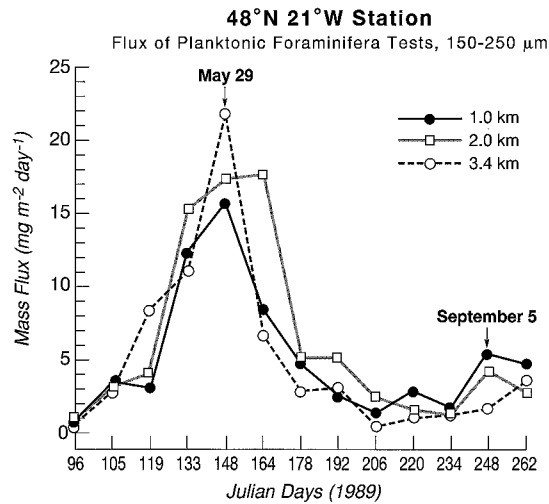


Figure 7.10 Flux of adult planktonic foraminifera tests (150–250 μm) at $48^\circ\text{N } 21^\circ\text{W}$ at three depths during the earlier half of 1989, showing no off-set of arrival time at deeper traps, indicating a rapid settling speed (Honjo and Manganini, 1993).

planktonic foraminifera tests with SST and hydrology (Curry et al., 1982; Deuser, 1986; Thunell and Honjo, 1989) such as pinpointing the timing of upwelling in the Arabian Sea (Curry et al., 1992).

Shanks and Trent (1990) and Alldredge and Gotschalk (1988) reported that the median *in situ* sinking rate of aggregates in the upper ocean (SCUBA depth) is about 50 to 100 m d⁻¹. The rates measured by *in situ* settling cylinders also suggested the rate is not as high as the ones estimated from the off-set of benchmarks (Asper, 1978; this volume). No explanation has been offered concerning why these two independent estimates give significantly different results. The excess density of upper ocean aggregates may be smaller than that of the deep ocean aggregates because of the former's fresher organic matter and less ballast.

A number of researchers have attempted to measure the descending speed of settling particles using several methods other than the off-set of benchmarks. For example, Lampitt (1985) observed the rate of arrival of plant detritus on the deep seafloor using a time-lapse camera, also collected very fresh detritus by tube corer, and compared its timing with the surface bloom. Asper (1987) measured the rate of arrival of settling particles at the bottom of a cylindrical sediment trap as well as from the side of a transparent *in situ* settling chamber using sequential photography. These experiments have resulted in settling speeds equivalent to the slow range of settling rates estimated by the off-set method mentioned above.

7.7.3 REVERSE ESTIMATE OF THE SUCCESSION OF AN UPPER OCEAN EVENT

Assuming that each settling particle carries "memory" of its production in the upper ocean by ecological and biogeochemical processes, and that it settles with relatively high speed at a known rate, the succession of events in the upper ocean can be estimated semiquantitatively by examining a set of time-series trap samples.

As an example, a scenario of an ecosystem sequence from the onset of the spring bloom (end of April) to the virtual cessation of surface productivity in late summer was estimated semiquantitatively at a North Atlantic station 48°N 21°W (Figure 7.11). The majority of sediment collected before May 29 (1989), consisted of fine particles which are apparently disintegrated amorphous aggregates and contained fewer fecal pellets of a size smaller than the annual norm. As previously mentioned, the sample collected from May 20 to June 6 contained a large number of adult foraminifera tests, resulting in a significant increase of carbonate flux during this period. A planktonic foraminifera bloom occurred rather early in the zooplankton bloom stage (Figures 7.10 and 7.11), but it is not clear whether, because of their fast settling speed, foraminifera tests arrived earlier than the fecal pellet flux maximum or plankton foraminifera are indeed the early birds when the bloom begins. Also diatom frustule flux reached maximum at the 2- and 3.7-km traps during the same period. The number and also the individual size of fecal

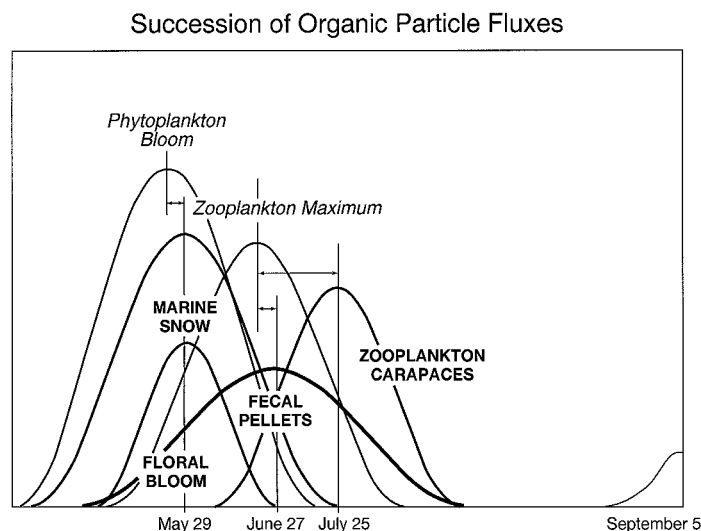


Figure 7.11 An example of qualitative reconstruction of ecosystem succession from flux samples collected in time series at a depth of 2 km during the bloom episode (48°N 21°W).

pellets in the sample increased, and this was maintained to late June, the end of the 1989 bloom episode. The two samples collected during the post-bloom episodes, August and September, contained a large number of zooplankton carapaces in the > 1 mm fraction. Samples from the latter period included chunks of gelatinous zooplankton; many were larger than 1 mm, but these were limited to the 1.2-km trap (Honjo and Manganini, 1992).

This observed sequence represents a text-book case of ecosystem succession in the open sea, showing the interaction between primary productivity, grazing, and removal from the upper layers (e.g., Peinert et al., 1987; Peinert et al., 1989; Heiskanen, 1990; Wassmann and Slagstad, 1990). First, an earlier spring phytoplankton bloom takes place in the thickened mixed layer when solar radiation is enhanced and water temperature elevated. The mass of phytoplankton is quickly removed from the surface layer to the ocean's interior as soon as the bloom starts. About the time of the maximum bloom at this station, grazing zooplankton become more dominant and advance their growth stages, becoming larger in size, as estimated from the increasing size and production of fecal pellets.

When nutrients are exhausted from the euphotic layer by phytoplankton and are totally removed from the euphotic layer, the zooplankton population is removed as large carapaces. As the final stage, in summer, the gelatinous zooplankton die and their carapaces arrive in the ocean's interior, but this large amount of fresh organic matter is more labile, is remineralized much more rapidly than normal settling particles, and does not arrive at deeper layers. Gardner et al. (1983)

observed that fresh labile ocean products degraded at rapid rates in the deep layers while they were exposed along moorings.

7.8 MESOSCALE EDDIES AND VERTICAL VARIABILITY OF FLUXES

Both the movement of eddies and the Lagrangian movement of settling particles are crucial for understanding the mass flux of particles in the deep ocean (Deuser et al., 1988; Siegel et al., 1990; Newell et al., 1994), particularly to explain the vertical variability of consecutive particle components such as CaCO_3 (Figures 7.8 and 7.9). In particular, mesoscale eddies of coccolithophorids such as reported by Holligan et al. (1983) from the North Atlantic, and Honjo (1982) from the Panama Basin, can be used to test the model in detail.

This model explains that if a depth-series sediment trap array is located right below the localized surface bloom, vertical flux would decrease with depth and increase with increased distance from the bloom. In the equatorial Pacific, a set of traps which were set 100 m apart at 2 km collected, for one year, almost identical mass fluxes in all particulate classes (Figure 7.3). This experience confines the term of Lagrangian diffusion, indicating that the source of particles is consistent. On the other hand, the deep ocean fluxes at two trap arrays in the mid Atlantic separated by about 100 km were almost indistinguishable during their main blooms. However, a peak of particle flux in the autumn of 1990 was far smaller at trap locations about 100 km away than at another location. This was interpreted as being caused by the shifting of a mesoscale eddy in this area at that time (Newton et al., 1994).

However, not all of the changes can be attributed to mesoscale eddy diffusion. Near the continent where a large quantity of fine bottom sediment is re-suspended by the boundary current, the flux increases significantly with depth (Honjo et al., 1983; Asper et al., 1992). It is conceivable that more quickly descending particles could catch up with the slowly descending particles below, resulting in an increase of flux by integrating produced particles which previously left the upper layers. In such a case, a benchmark of settling particles does not represent the productive event. A deep-ocean marine snow camera has captured many zones where settling particles are far more concentrated in a water column (Asper et al., 1992). Alternating dense and thin clouds of marine snow are often visible from the portholes of descending deep-sea submersibles. Beside a pulsing supply of settling particles from the source (Asper et al., 1988), such zonal or vertically uneven distribution of settling particle density can also be produced by a difference in settling speed.

7.9 ALTERATION OF SETTLING PARTICLES