TEMPORAL VARIABILITY OF PARTICLE FLUX

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Introduction

Until the late 1960s the deep ocean was considered the least variable environment above the solid surface of the earth. It is always cold and dark, and no expressions of the diurnal or annual cycles shaping the subaerial environment were expected to penetrate the ocean beyond a depth of a few hundred meters. It was also believed that the fine particles constituting the bulk of deep-sea sediments took years to reach the seafloor. Then, in the 1970s and early 1980s, several lines of evidence contradicting this view emerged: what appeared to be annual varves were detected in the sediments of the Black Sea at a depth of more than 2000 m, and annual reproduction cycles and growth bands were reported for a few deep-benthic organisms. A plausible explanation for such periodicity in the deep sea was lacking, however, until time-series measurements by deep-ocean sediment traps at a depth of 3200 m in the Sargasso Sea revealed seasonal changes in the flux of particulate organic matter and, indeed, of all types of sedimenting particles. The variability of the deep flux could be attributed to changes in primary productivity in the euphotic zone about 1 month earlier. This finding demonstrated how unexpectedly rapid the transport of particles to the deep sea is and provided evidence for a seasonally variable food supply for deep-benthic organisms. Such variable food supply fosters uneven growth rates and cyclic reproduction.

Ubiquity of Temporal Flux Variations

Time-series measurements of the sinking particle flux in many parts of the oceans and marginal seas have consistently revealed significant temporal variations. A partial listing includes the north-eastern, eastern, and central North Pacific, the Panama Basin, the Gulf of California, the Equatorial Pacific, the Greenland and Norwegian Seas, the north-eastern North Atlantic, Bay of Biscaye, Mediterranean, Sargasso Sea, the Atlantic off West Africa, the Caribbean Sea, the eastern Equatorial Atlantic, the Walvis Ridge off Namibia, the Bransfield Strait, the Weddell Sea, the Arabian Sea, and the Bay of Bengal. No doubt, other parts of the ocean will be sampled in the future and, most likely, temporal variations in particle flux will be found.

Reality of 'Temporal' Flux Variations

Variations in the amount of sinking material per unit time recorded by stationary sediment traps in reality are convolutions of three components: (1) true temporal variations in the sinking flux, (2) spatial variations in the distribution of sinking particles moving past the trap site, and (3) variations in the retention efficiency of the traps caused by changes in trap tilt and ambient current speed. To some extent, the magnitudes of the second and third components can be reduced by the use of free-floating, neutrally buoyant traps, but the difficulties of deploying them at the desired depths and of tracking and recovering them have as yet prevented their widespread use.

Further complications in interpreting apparent temporal flux variations recorded by stationary traps are introduced by the different sinking speeds of particles, typically ranging from 50 to > $500\,m\,d^{-1}$. Rapidly sinking particles intercepted by traps carry signatures of conditions in overlying waters in a more recent time interval than do slowly sinking ones. This effect leads to both a mixing and 'smearing' of the real temporal variations of different particle classes prevailing during their departure intervals at or near the surface (**Figure 1**). In addition, apparent changes in flux measured during successive sampling intervals of a given length (e.g. 15 d) in reality represent variations in near-surface conditions over significantly longer intervals (**Figure 2**). Nevertheless, some new and important insights into the inner workings of the ocean have been gained through the use of sediment traps.

Causes of Flux Variability

A variety of processes lead to variability in the flux of particulate matter to the seafloor. Variations in primary productivity in surface waters owing to seasonal (and shorter-term) changes in mixed-layer depth and attendant replenishment of nutrients in the euphotic zone are the primary cause of flux variations to the deep oceans of the temperate and subtropical latitudes. Intense storms, such as hurricanes, can also create localized flux pulses along their tracks. Dust storms, as emanating from the western Sahara and reaching far across the Atlantic, for example, create pulses of lithogenic flux components in their wake. Iron, a growth-limiting micronutrient associated with the dust particles, can stimulate a primary production spike, especially of diatoms which, in turn, may boost the sinking flux of opaline silica and zooplankton fecal material and skeletal remains. The seasonal monsoons affecting the northern Indian Ocean have been shown to influence the primary production and flux of particles to the deep Arabian Sea and Bay of Bengal. Seasonal changes in flow of tropical rivers cause fluctuations in the supply of nutrients to their plumes and can cause seemingly erratic fluctuations in productivity and particle export as far as hundreds to thousands of kilometers from the river mouths. The annual cycle of waxing and waning ice cover on high-latitude oceans influences the amount of sinking material. Variations in upwelling intensity on seasonal to multiannual timescales result in concomitant variations in sinking flux.

Timescales of Flux Variability

Knowledge of timescales of flux variability is limited by the sampling schemes designed to intercept the sinking flux of particles. While in all likelihood particle fluxes vary on timescales as short as minutes or less, the practicality of sampling measurable amounts in the deep ocean has placed a lower limit of daily sampling intervals on attempts to determine variability. Also, inasmuch as appropriate technology became available only in the late 1970s and only a few sites have been sampled for even a single decade, detection of true decadal variability thus far is restricted to decade-length trends only. There is no way of knowing whether such trends are parts of continuing unidirectional changes or parts of long-term cycles. It is fair to say, however, that flux variability has been found wherever and whenever attempts were made to detect it. At least at one site in the Sargasso Sea it has been documented on timescales from diurnal to decadal. Evidence for

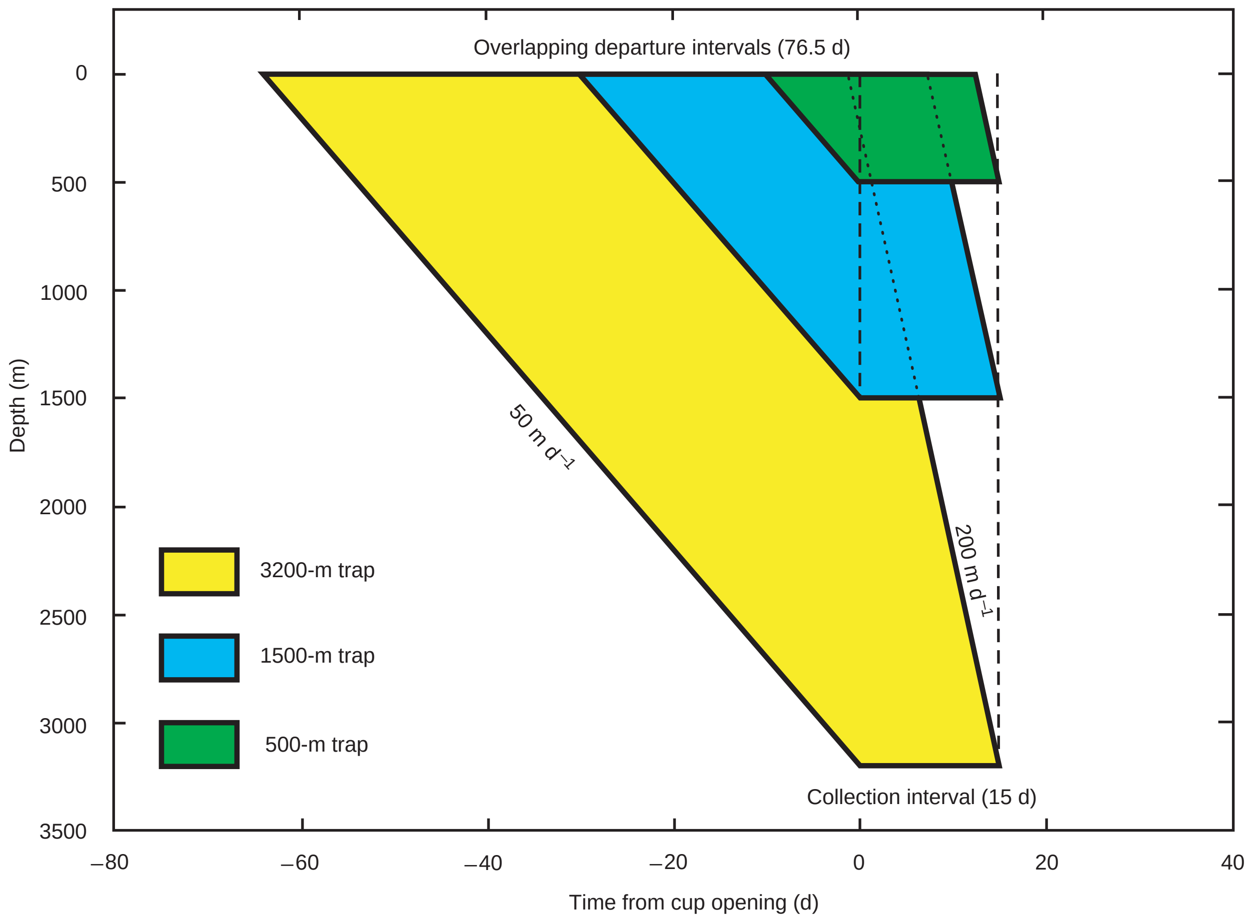

Figure 1 Schematic illustration of the different time intervals of surface departure of particles with different sinking speeds sampled simultaneously by a deep-ocean sediment trap. (Reprinted from *Deep-Sea Research I*, 44, Siegel and Deuser, Trajectories of sinking particles in the Sargasso Sea: modeling of statistical funnels above deep-ocean sediment traps. pp. 1519–1541, copyright (1997) with permission from Elsevier Science.).

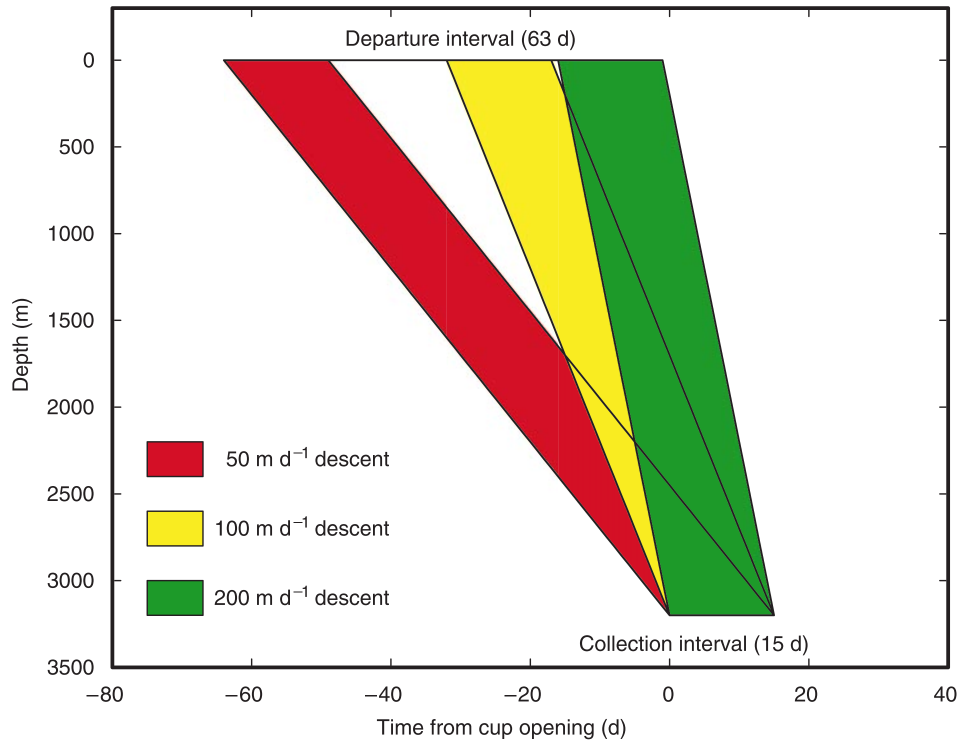

Figure 2 Schematic of the overlapping, but widely different, time intervals which were sampled simultaneously by an array of three sediment traps at different depths on the same mooring. (Reprinted from *Deep-Sea Research I*, 44, Siegel and Deuser, Trajectories of sinking particles in the Sargasso Sea: modeling of statistical funnels above deep-ocean sediment traps, pp. 1519–1541, copyright (1997) with permission from Elsevier Science.)

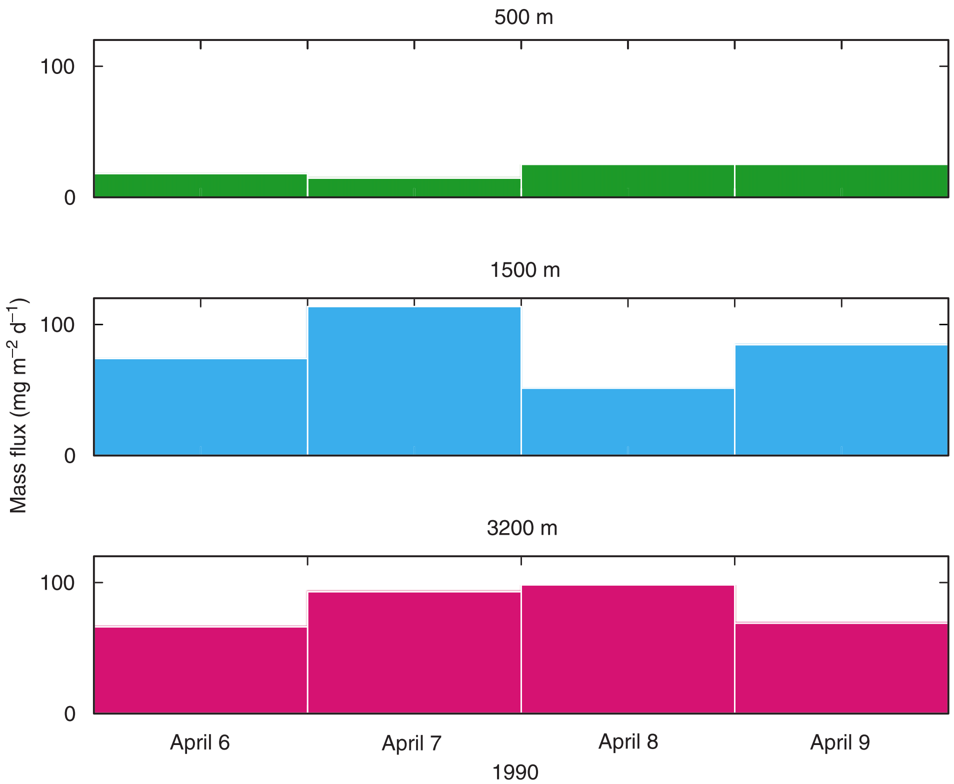

Figure 3 Example of daily mass flux differences at three depths in the Sargasso Sea. Note that the three traps sampled particles which departed the upper ocean at different times (compare with **Figure 2**).

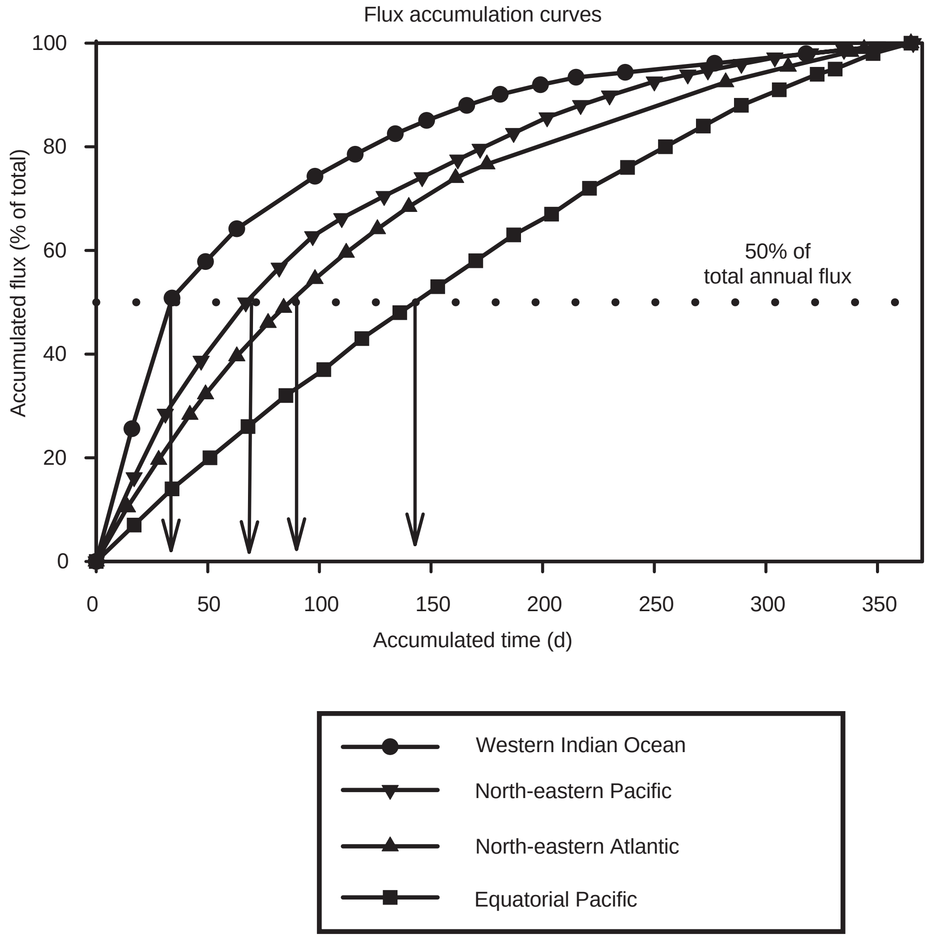

Figure 4 Yearly cumulative flux curves for four oceanic provinces. (Reprinted from *Deep-Sea Research I*, 44, from Lampitt and Antia, Particle flux in deep seas: regional characteristics and temporal variability, pp. 1377–1403, copyright (1997) with permission from Elsevier Science.).

even longer-term variability of sediment flux, on timescales of centuries and beyond, is found in the sedimentary record of a great many geological periods.

Diurnal

Diurnal flux variability is the rule in the upper ocean due to such causes as patchiness in the distribution of particle-producing organisms, eddies, day-to-day differences in solar heating, and wind speed. For technical and logistical reasons, there is less documentation of diurnal flux variability in the deep ocean. An example of this flux at three depths on the same mooring in the Sargasso Sea is shown in **Figure 3**. Even at a depth of 1500 m daily fluxes varied by a factor of two.

Monthly

There are hints of a lunar cycle (29.5 d). in some sediment trap records. Some organisms, such as planktonic foraminifera, have lunar reproduction cycles which ought to find an expression in the sinking flux of their skeletal parts. The difficulty in demonstrating lunar cyclicity in the flux intercepted by sediment traps lies in devising sampling schemes which avoid aliasing of the lunar period. With the widely employed monthly or semimonthly sampling frequency of traps this is not possible.

Seasonal

The most widely detected temporal variation in the sinking flux is seasonal, i.e. an annual cycle. The practical reason for this is that the cycle of seasons fits best into the sampling schemes suitable to remote locations and into the funding schemes of agencies supporting oceanographic research. The fundamental reason is that all parts of the ocean, including those at tropical latitudes, are subject to seasonal changes. Insolation, sea surface temperature, wind speed and direction, precipitation, and

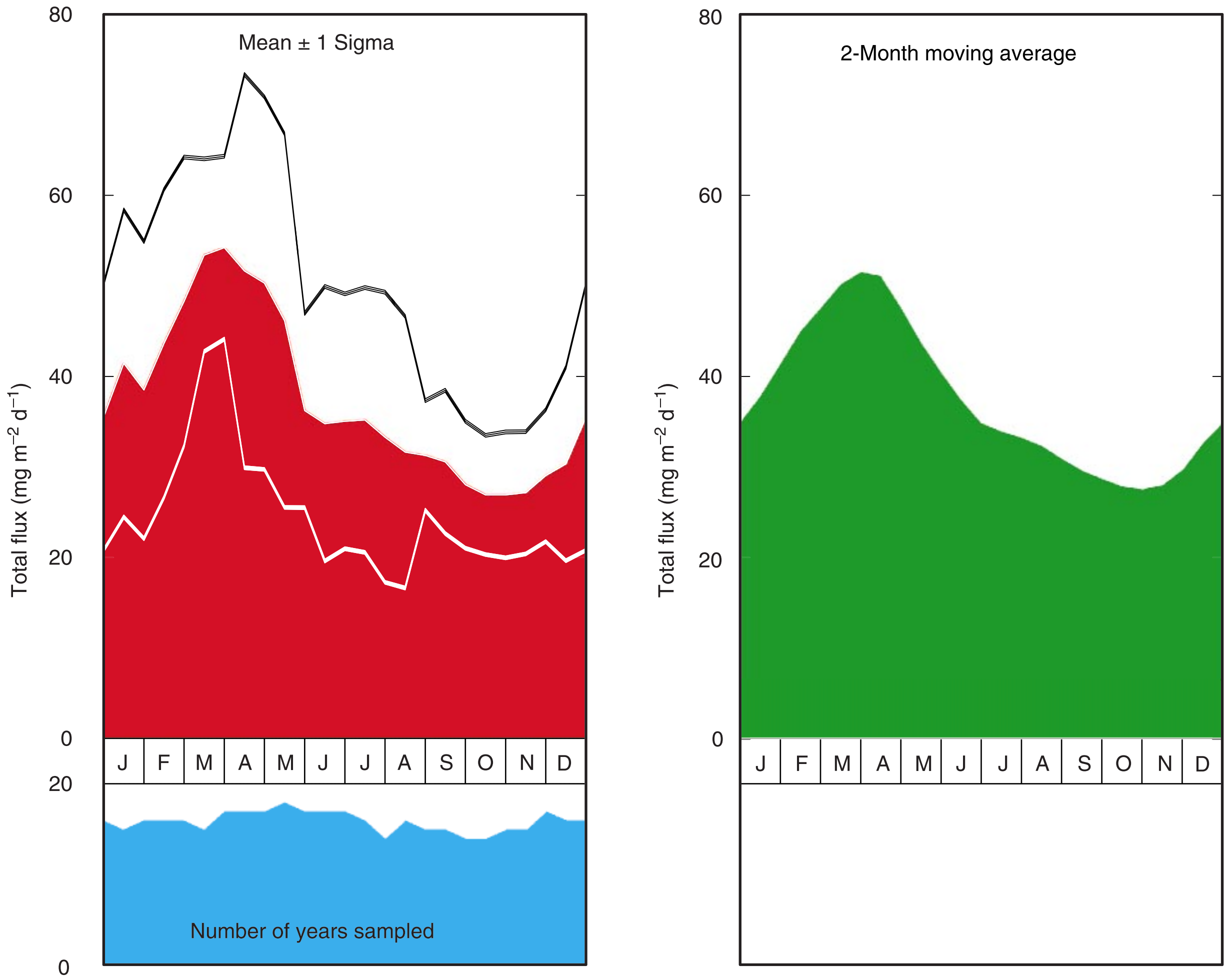

Figure 5 Average annual flux variation over a period of 18 years (1978–95) at 3200 m in the Sargasso Sea. The standard deviations around the semimonthly averages in the left panel give an indication of the interannual variability. The small panel at lower left indicates the number of years for which measurements were made at beginning and middle of each month.

in some parts ice cover and surface currents, as well as human activities, all undergo seasonal changes. All of these factors have some bearing on biological productivity and/or detrital input into the surface ocean.

Amplitudes of the annual cycle differ widely in different parts of the ocean. In the high latitudes, where the ocean is ice-free for only a short time, half of the annual particle flux may be delivered to deep water in a month or less. Annual cumulative flux curves for four different open-ocean regimes, calculated for a standard depth of 2000 m, are shown in **Figure 4**. In general, the lower the latitude, the less pronounced the annual cycle, but areas such as the Arabian Sea, which is strongly affected by the seasonal monsoons, deviate from this pattern.

The longest series of consistent measurements of the particle flux to the deep ocean is for a depth of 3200 m in the Sargasso Sea. The average annual cycle and its standard deviation over a period of 18 years for that site are shown in **Figure 5**. The cycle is quasi-sinusoidal, but there are several features worthy of note, as follows. (1) On average, even at the time of lowest flux, i.e. in the fall, the flux is still about half that at the time of maximum flux. (2) The greatest variance (a measure of interannual variability) occurs at the time of maximum flux, i.e. in the spring, followed by a secondary maximum in midsummer. Conversely, the lowest variance occurs at the time of lowest flux. (3) The transition from the autumnal flux minimum to the vernal flux maximum is not sudden, as might be expected based on a rather sudden spring bloom, but gradual. The reason for this is that there are actually a number of mixing events triggering minor blooms which increase in frequency and build up to one or several major blooms in spring.

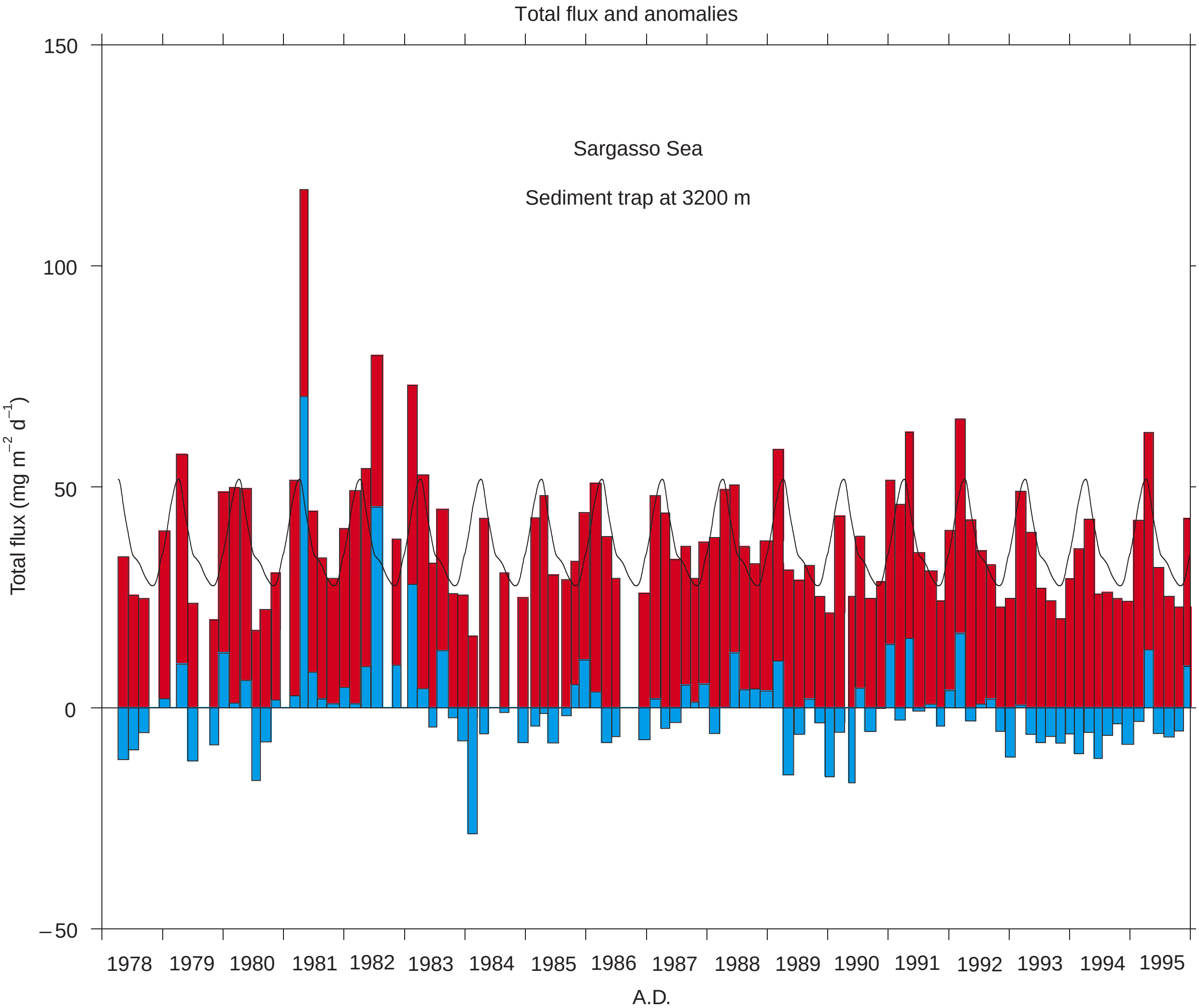

Figure 6 An 18-year record of bimonthly flux variations at 3200 m in the Sargassso Sea. Column heights indicate total mass flux, blue sections indicate the anomalies relative to 18-year average, as shown by the wavy line and the right panel of **Figure 5**.

Interannual

Interannual variability has been detected wherever the sinking flux has been sampled for several years. It appears that everywhere in the deep ocean every year is different from every other year. The interpretation of such variability, however, is anything but clear-cut. In some instances interannual flux differences have been attributed to ENSO, when the sampling periods serendipitously encompassed an El Niño and either a preceding or subsequent period. However, little confidence can be placed in such a causal relationship until and unless it has been shown to hold through several El Niño periods. One of the difficulties in demonstrating a connection is the fact that El Niño periods occur irregularly on a pentadal to sub-decadal timescale and that long-term sampling schemes are difficult and expensive to execute. Thus far there are fewer than a half-dozen sites in the world's oceans where the sinking flux has been continuously sampled for more than a couple of years.

The true measure of interannual variability is best expressed as anomalies, i.e. flux deviations over the length of a sampling period from the multi-year average flux over that same period. **Figure 6** shows bimonthly anomalies at the Sargasso Sea site for a period of 18 years. It is apparent that the first half of the record was 'noisier' and contained more positive anomalies than the second half which was 'quieter' and had predominantly negative anomalies. Whether this change is part of a decadal cyclicity (as evident in some climatic oscillations), part of a unidirectional trend, or mere random variability, cannot be ascertained. The power spectrum of the anomalies (**Figure 7**) shows weak peaks at periods

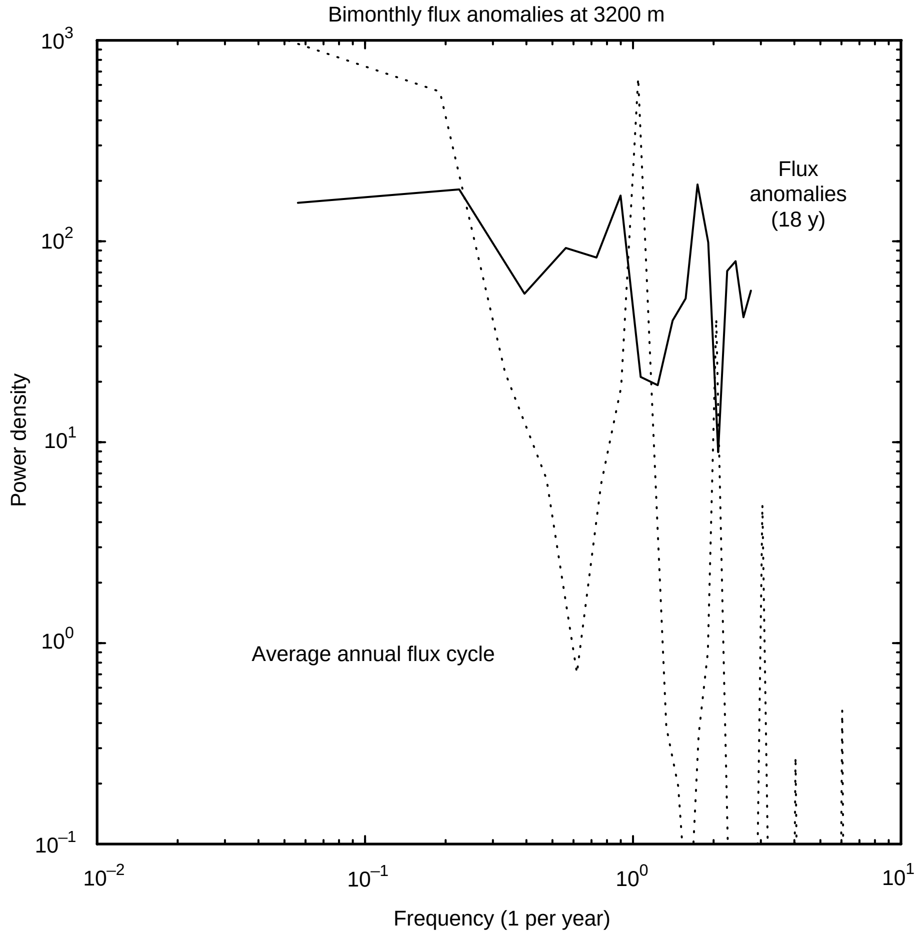

Figure 7 Power spectrum of the anomalies shown in **Figure 6** (solid line) compared with that of the average annual flux cycle (dotted line). There are no significant peaks for periods longer than 1 year.

of approximately 0.6, 1.1, and 4.5 years, with the latter not being significant. This demonstrates clearly that patterns of multiannual variability can be detected only in sampling records of duration far exceeding those presently available.

Decadal

True decadal variability is detectable only in time-series of several decades' length, but trends may become apparent in shorter series. An example is a significant 14-year negative trend in the opal/calcium carbonate ratio in the sinking material in the Sargasso Sea (**Figure 8**). It appears that changes in the species assemblage of the silica-producing biota were responsible for the trend. But, while the trend parallels a significant trend of increasing wind speed in the Bermuda area, a causal connection between the two is not obvious.

A 7-year trend of decreasing flux of particulate organic carbon was detected in the deep eastern North Pacific. In that case the trend was attributed to a long-term increase in the temperature of the upper water column which, in turn, led to decreases in mixed-layer depth, nutrient supply to the euphotic zone, and primary production. Thus it appears that here, too, climatic change, whether of cyclic or unidirectional nature, affects the flux of particles to the deep ocean.

Episodic

There is increasing evidence that episodic or 'unusual' events, i.e. events that fall outside the norm of commonly observed variability, can have significant and enduring effects on ecosystems and the sedimentary record. The question of what constitutes an unusual event, however, is not trivial. The evidence suggests that the frequency of such occurrences decreases, rather than increases, with increasing length of a series of observations or measurements. In other words, the lack of a long-term perspective causes the observer to attribute a deviation from the short-term norm to an unusual event although the longer-term norm may well encompass deviations of this magnitude. Even more

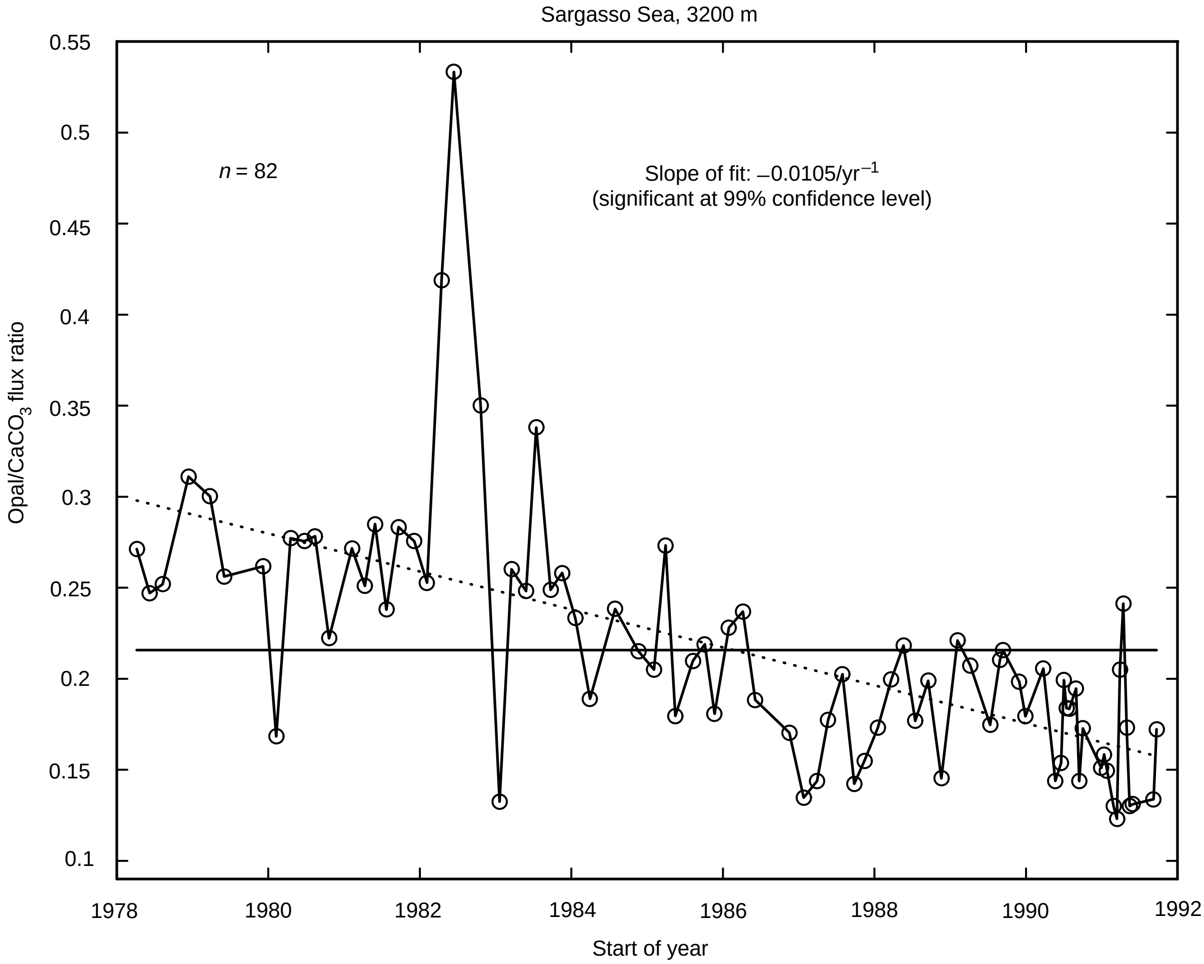

Figure 8 The 14-year record of variations in the ratio of opaline silica to calcium carbonate in material sinking to the deep Sargasso Sea. The overall trend of a decrease in the ratio (dotted line) is probably due to changes in the species assemblage of opal-producing biota which, in turn, could be related to a subtle climatic trend over that period. (Reprinted from *Deep-Sea Research I*, 42, Deuser, Jickells, King and Commeau, Decadal and annual changes in biogenic opal and carbonate fluxes to the deep Sargasso Sea, pp. 1923–1932, copyright (1995) with permission from Elsevier Science.)

difficult is the assignment of likely causes to such events. There is a general lack of simultaneous, continuous monitoring of meteorological and oceanographic variables to identify chains of events which might trigger episodic peaks in the sinking flux. Even closely spaced snapshot measurements of those variables stand a good chance of missing the brief conditions initiating the chain. An example is the record of an event of very high coccolith flux in the Panama Basin. The flux during one of six bimonthly collection periods exceeded by orders of magnitude the flux observed during the other five. Most likely, the defining event was much shorter than 2 months, suggesting an even more pronounced transient. However, the lack of appropriate concurrent measurement series precluded the assignment of a likely cause to the event. It is hoped that with increasing recognition of the value of time-series measurements and with the trend towards developing instrumentation capable of long-term automated monitoring of meteorological and hydrographic variables it will become easier both to detect and identify the causes of unpredictable episodic events.

Conclusions

Except near hydrothermal vents, the sinking flux of particles – whose formation ultimately depends on photosynthesis – provides the fuel for all life forms in the deep ocean. It is becoming increasingly clear that this 'rain' varies on all timescales up to decadal and beyond. The deep ocean is thus not in a steady state and its life forms are quite closely coupled to both gradual changes and sudden events near the surface.

See also

Primary Production Distribution. Primary Production Methods. Primary Production Processes. River Inputs. Trapped Particulate Flux. Upper Ocean Mixing Processes. Upper Ocean Time and Space Variability.

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THERMAL DISCHARGES AND POLLUTION

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Sources of Thermal Discharges

The largest single source of heat to most water bodies, including the sea, is the sun. Natural thermal springs also occur in many parts of the world, almost all as fresh water, some of which discharge to the sea. In the deep oceans hydrothermal vents discharge mineral-rich hot water at temperatures greatly exceeding any natural temperatures either at depth or at the surface. To add to these natural sources of heat, industrial processes have discharged heated effluents into coastal waters in many parts of the world for at least 150 years. By far the largest volumes of these heated effluents reaching the sea in the past 60 years have originated from the electricity generation industry (power industry). Indeed more than 80% of the volume of heated effluents to the sea originate from the power industry compared with 3–5% from the petroleum industries and up to 7% (in the USA) from chemical and steel industries.

The process known as 'thermal' power generation, in which a fuel such as oil or coal or the process of nuclear fission is used to heat water to steam to drive turbines, requires large volumes of cooling water to remove the waste heat produced in the process. Where power stations are sited on or near the coast all of this waste heat, representing some 60–65% of that used in the process, is discharged to the sea. The heat is then dissipated through dilution, conduction, or convection. In a few, atypical coastal situations, where the receiving water does not have the capacity to dissipate the heat, artificial means of cooling the effluent such as ponds or cooling-towers are used. Here the effluent is cooled prior to discharge and much of the heat dissipated to the air.

The waste heat is related to the theoretical thermal efficiency of the Rankine cycle, which is the modification of the Carnot thermodynamic cycle on which the process is based. This has a maximum theoretical efficiency of about 60% but because of environmental temperatures and material properties the practical efficiency is around 40%. Given this level of efficiency and the normal operating conditions of a modern coal- or oil-fired power station, namely steam at 550°C and a pressure of 10.3×10^6 kg cm^{-2} with corresponding heat rates of 2200 kg cal kWh^{-1} of electricity, some 1400 kg cal kWh^{-1} of heat is discharged to the environment, usually in cooling water at coastal sites. This assumes a natural water temperature of 10°C. Nuclear power stations usually reject about 50% more heat per unit of electricity generated because they operate at lower temperatures and pressures. Since the 1920s efficiencies have increased from about 20% to 38–40% today with a corresponding reduction by up to 50% of the rate of heat loss. The massive expansion of the industry since the 1920s has, however, increased the total amounts of heat discharged to the sea.

Thus for each conventional modern power station of 2000 MW capacity some 63 $m^3 s^{-1}$ of cooling