The Oceanic Flux Program

Twenty Years of Particle Flux Measurements in the Deep Sargasso Sea

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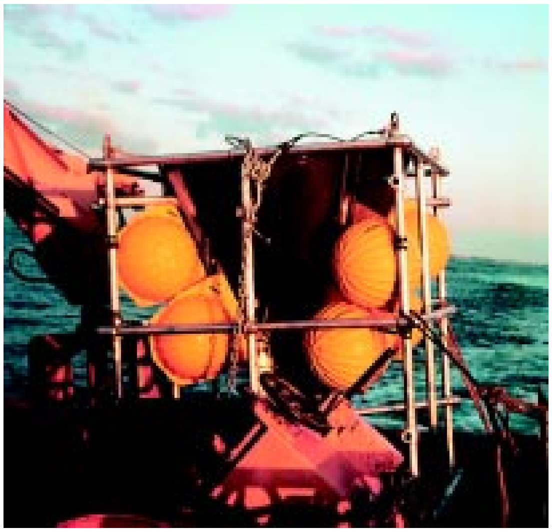
October 1997: Deployment of the Oceanic Flux Program sediment trap mooring aboard R/V *Weatherbird II* (Bermuda Biological Station). Sinking material will be collected in the sample bottles on the rotating plate affixed to the bottom of the trap funnel. The large yellow balls are "hardhats" housing glass deep sea floats.

October 14, 1997: The predawn hours at sea have a unique feel—an eerie stillness, regardless of weather. This morning is no exception as the Bermuda Biological Station's R/V *Weatherbird II* approaches the OFP (Oceanic Flux Program) sediment trap mooring some 75 kilometers southeast of Bermuda.

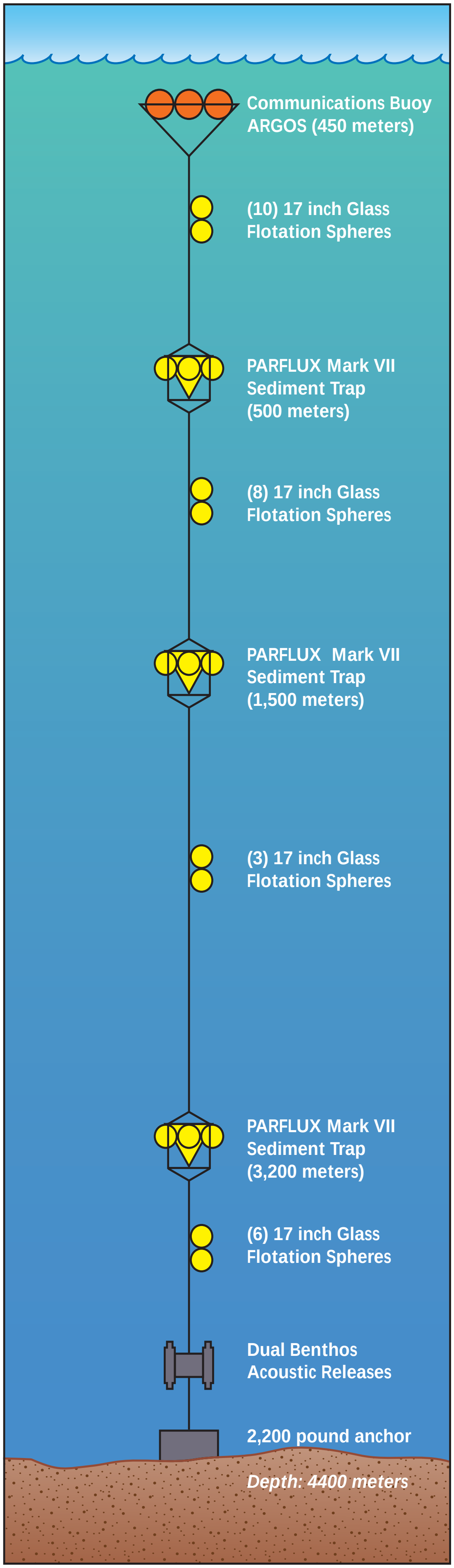


May 1977: Werner Deuser's first sediment trap is ready for its initial entry into the sea. The ship's crane was used to lower this large trap into the water.

The top of the mooring is subsurface, so we rely on the ship's GPS (Global Positioning System) navigation to locate the exact mooring position. There's a small ground swell, a freshening breeze, and a sliver of yellow moon setting as we lower the acoustic transducer over the starboard beam. After presetting the deck unit with appropriate frequencies, I send interrogation signals to one of two releases near the bottom of the mooring—a distance of four thousand meters below the sea surface. The deck box light flashes, indicating receipt of the release's acoustic response, and the range is displayed on the readout. Thanks to GPS, we are directly over the mooring.

I communicate with the releases a few more times to confirm distance and then switch frequencies to command one of the releases to retract a pin that holds it fast to the anchor line. A double flash on the deckbox indicates an affirmative response from the signaled release, and the mooring, free of its anchor, begins to ascend. When it reaches the surface, the communications buoy transmits a radio signal and its strobe begins to flash. We head to the bridge deck where we earnestly scan the horizon for

The Oceanic Flux Program (OFP) sediment trap mooring is four kilometers long and consists of three sediment traps, deep sea floats, dual acoustic releases and a communications buoy. The buoyancy along the mooring string is carefully engineered to keep the mooring vertical and to ensure that it comes up tangle free when recovered.



Jack Cook

the strobe and listen for the radio signal.

On target—success! Strobe off the port bow! Sediment traps bobbing in the swell! With smiles of relieved anxiety, we mark position and wait for full daylight to commence the 98th recovery of the OFP sediment trap mooring.

Over 20 years earlier, WHOI geochemist Werner Deuser first deployed his deep ocean sediment trap in this area near the site of the longstanding Hydrostation S time series (see *Oceanus* Vol. 39, No. 2 for an article on Station S). Advances in deep ocean mooring technology had just made it possible for Deuser and others to directly sample the rain of particles falling in the abyssal ocean by using large conical or cylindrically shaped sediment "trap" collectors. Deuser's first sediment trap was a monstrous instrument having a 1.5 square meter cross section at the funnel aperture and a single sample collection bottle at the base. After two months of sampling, the mooring was retrieved and the trap redeployed with a fresh collection bottle. A combination of rough open ocean waters and a research vessel measuring merely 65 feet (Bermuda Biological Station's R/V *Panulirus II*) made sample collection particularly arduous. But Deuser, with assistance from the Bermuda Biological Station, persisted with this grueling mooring turnaround schedule for many years. His efforts produced the first continuous time series of particle flux in the deep ocean.

By the early 1980s, Deuser surprised the oceanographic community with the observation that the amount of material sinking through the deep ocean was not constant but varied seasonally with the cycle of phytoplankton production in the overlying surface waters. This discovery directly contradicted the widely held belief that the deep ocean was a highly stable, unchanging environment. In fact, the particle flux record revealed that the deep ocean environment was quite variable and tightly coupled to upper ocean processes via a rapid delivery of particles from the surface within a time span of just a few weeks. And not only did the deep ocean flux of biogenic materials—skeletal parts of microscopic plants and animals, fecal pellets, and amorphous organic matter—vary seasonally. Nonbiological materials such as dust also varied in concert with the biogenic flux, despite differences in the timing of the dust deposition at the sea surface. It appeared that animal grazers in the surface ocean were extremely efficient at scavenging dust and other suspended particles from the water column and "repackaging" this material into larger particles that sank more rapidly. This enhancement of particle flux by biological scavenging activities is now known to be essential in the geochemical cycling of carbon and associated elements in the ocean and has been loosely termed the "biological pump."

The OFP time series, like the world around us, has undergone a few changes since 1977. The large, crude, original sediment trap has been replaced by smaller, microprocessor-controlled traps capable of collecting a sequential set of samples at accurately timed intervals in a single deployment. To address questions pertaining to the downward flux of material, we have added to the mooring new traps at 500 and 1,500 meter depths. New technologies such as GPS navigation, ARGOS satellite tracking systems, and improved acoustic releases have greatly simplified and reduced the risks associated with deploying and retrieving deep ocean moorings. Advances in laboratory instrumentation now allow detailed chemical analyses that were unimaginable when the program began and that require only minute quantities of recovered material. There have also been changes in personnel and new directions: In 1996 Deuser retired and passed the leadership of the program to me. Yet, throughout the changes of the last 20 years, an OFP sediment trap has continuously sampled the deep particle flux at this site in the Sargasso Sea.

The particles landing in a deep sediment trap may have originated at the surface over a hundred kilometers away. Statistically, the catchment area of the OFP 3,200 meter trap is representative of thousands of square kilometers of surface ocean. Deep sediment traps provide a spatially and temporally integrated picture of ocean functioning that cannot easily be assessed by other types of samplers, such as water bottles, because these measure only a "snapshot" in space and time. The OFP record shows that particle flux in the deep Sargasso Sea has varied on a number of time scales, from short-lived, episodic, high-flux "events" lasting only days to a few weeks to interannual and longer term trends spanning more than a decade.

The time series, particularly the biweekly resolved flux record collected since 1989, shows marked year to year variability in the magnitude and timing of the seasonal flux maximum that is associated with the annual spring peak in phytoplankton production. Our research aims not only to measure variability in flux, which has significant implications for the biogeochemical cycling of carbon and associated elements, but also to understand the underlying causes of this variability and the relationship to upper ocean processes. This goal has been greatly assisted in recent years by the addition of other research programs in the overlying waters near the OFP site, including the US-Joint Global Ocean Flux Study Bermuda Atlantic Time-Series program of upper ocean biogeochemistry and physics, and the Bermuda Testbed Mooring, which contains a suite of novel and sophisticated instruments continuously measuring physical, chemical, and bio-optical properties of the upper water column. These programs, coupled with the deep ocean measurements, are helping to illuminate the complex dynamics linking upper ocean physics and biology to particle flux in the deep ocean.

The OFP sediment traps collect from ten to a hundred grams of material during a typical two week sampling interval. Overall, the bulk composition of this material is remarkably consistent. About 70 percent of the sinking material at 3,200 meters consists of carbonaceous or siliceous shells of minute animals such as foraminifera, radiolarians, and pteropods, and the skeletal remains of single cell algae such as the coccolithophores, diatoms, and dinoflagellates. Although a few individual shells are large enough to sink unabated, most of the skeletal material consists of smaller particles and fragments that have been incorporated into larger, more rapidly sinking zooplankton fecal pellets or

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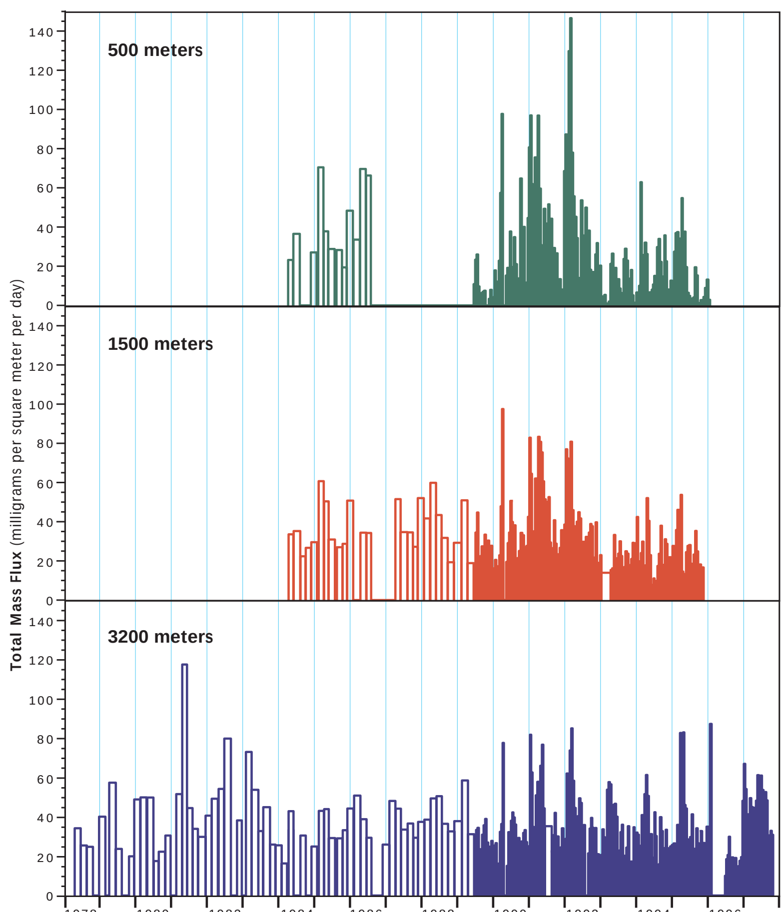
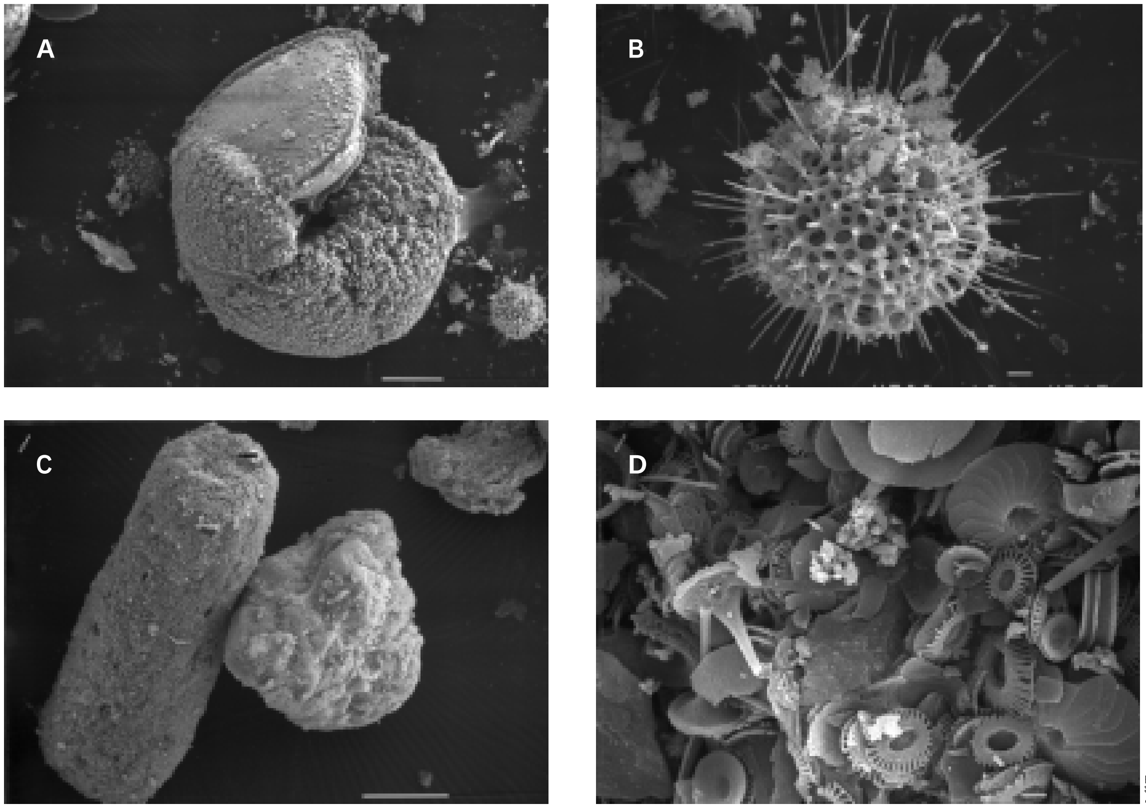
Werner Deuser is shown here aboard R/V *Atlantis II* in 1977, the year that he initiated the first continuous time series of particle flux measurements in the deep ocean.



The Oceanic Flux Program particle flux record in the Sargasso Sea. The present time series is today one of the very few oceanographic time series extending for more than a decade and by far the longest record of its kind.



Scanning electron micrographs of typical components of the particle flux material collected by the 3,200 meter Oceanic Flux Program trap. (A) A calcite shell of a foraminifer (a one-celled animal) with secondary calcite encrustations. The species composition and carbon and oxygen isotopic ratios of foraminifera shells preserved in ocean sediments are extensively used by paleoceanographers to reconstruct the past ocean environment. (B) A siliceous test of a radiolarian, another one-celled animal. (C) A zooplankton fecal pellet (left) and an unidentified biological aggregate. (D) Assorted skeletal remains of coccolithophorids, diatoms, dinoflagellates, and amorphous organic material aggregated inside the elongated fecal pellet shown in C. The elaborate round structures are individual calcite plates (liths) from different coccolithophore species.

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amorphous biogenic material. Only about 12 percent of the material by weight is organic, as the majority (more than 95 percent) of organic material synthesized in the surface ocean is consumed before reaching the deep ocean. The remaining 18 percent of the trap material consists largely of clays and other minerals derived from atmospheric dust deposition and/or long range horizontal transport of resuspended ocean sediments.

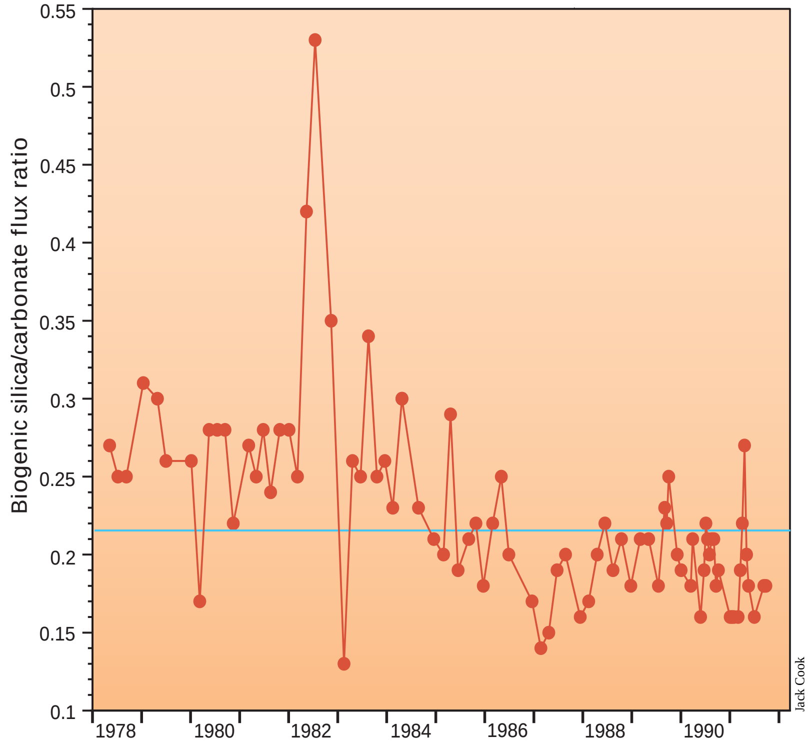
One intriguing finding is the existence of small, yet highly significant, long-term trends in the bulk composition of the sinking skeletal material at 3,200 meters. An overall 50 percent decrease in the biogenic silica to carbonate flux ratio from 1978 to 1991 is superimposed upon pronounced seasonal flux cycles of biogenic carbonate (synthesized by coccolithophorids and foraminifera) and silica (synthesized by radiolaria and diatoms). This decrease was due primarily to a reduction in the biogenic silica flux. The morphology of the siliceous particles changed during this period, suggesting that the species composition of silica-producing organisms in the overlying surface waters had changed. A significant (24 percent) increase in mean wind speed at Bermuda coincided with the change in deep biogenic silica flux. This led Deuser to hypothesize that small changes in physical forcing at the sea surface had induced significant changes in the surface ocean ecosystem, which in turn altered the makeup of export fluxes.

How do we relate what is captured in the sediment trap to the upper ocean processes that control vertical flux? Resident within the sinking material are inorganic and organic chemical signals that contain a wealth of information on the sources of the material and the subsequent processes that have influenced its flux. Often the flux pattern of a trace constituent may be drastically altered when one of the processes is varied, even though there is only an insignificant change in the bulk composition. We, and other researchers with whom we collaborate, analyze the OFP trap material for a variety of trace chemical constituents to unravel its history.

Our laboratory focuses on analysis of key organic compounds, or "biomarkers," using trace organic extraction methods, followed by gas chromatography and mass spectrometry, to identify and quantify nanogram (one-billionth of a gram) quantities of the target compounds in our samples. Recently, we analyzed the lipid (fatty organic) biomarker composition of trap material collected prior to, and during, an episodic flux "event" that occurred in January 1996 to determine the cause of this abrupt increase in flux. The lipid biomarker composition of sinking material collected just before the event indicated that this material was extensively degraded. However, the organic material collected during the high flux event was greatly enriched in labile (unstable) phytoplankton-derived biomarker compounds as well as in bacteria-derived biomarkers, indicating that it consisted of relatively fresh phytoplankton debris being actively degraded by bacteria. These biomarker results strongly suggest that this episodic high flux event resulted from a short-lived phytoplankton bloom in the overlying waters that was inefficiently degraded in surface waters and settled to depth rapidly. The persisting question is: How much of the observed increase in deep flux is due to increased production, and how much may be due to an increased efficiency of material transfer through the upper ocean?

Our findings suggest that the flux of labile, biologically available carbon and easily remineralized elements to the deep ocean underlying waters of low productivity may be more episodic than previously appreciated. At the OFP site, some of these events appear to be meteorologically driven by transient weather conditions affecting the influx of production-stimulating nutrients into the sunlit zone and the subsequent mixing of the resulting products into deeper waters. If this hypothesis proves correct, then changes in global climate should significantly affect export fluxes to the deep ocean—especially changes affecting wintertime storm patterns, such as the North Atlantic Oscillation (see *Oceanus* Vol. 39, No. 2).

What new insights from the OFP time-series can we expect in the future? The record to date shows subtle yet highly significant oceanographic trends against a background of large, and sometimes seemingly random, variability. Such trends can be detected only through continuous and carefully repeated measurements over a long period of time. To fully understand the multiyear and quasi-decadal cycles requires careful observation for perhaps an additional 20 years. As we progress in our long-term objective to assess interannual to decadal variability in material fluxes to the deep ocean, our goal is to interpret the temporal trends we observe in terms of changes in overlying ocean ecosystem functioning and in the atmosphere/climate system. This goal is of paramount importance for predicting the ocean's response to future, possibly anthropogenically induced, climate changes.



The long-term trend in the biogenic carbonate to silica flux ratio in the 3,200 meter Oceanic Flux Program trap. Variability in the deep particle flux appears to be forced by large scale changes in the atmosphere/ocean climate system.

The OFP time-series has been supported throughout by the National Science Foundation, with additional funding for the organic biomarker analyses from the Petroleum Research Fund.

Maureen Conte is an organic geochemist who uses trace lipid biomarker compounds to elucidate organic carbon pathways in the ocean and atmosphere. Before coming to WHOI in 1994 to succeed Werner Deuser as head of the Bermuda time series, she spent five cold and damp years in Britain, where she studied carbon cycling processes in the high latitude North Atlantic. She is also an accomplished musician who has traveled the US and Caribbean entertaining others with old-timey and Celtic melodies. When not in Bermuda (her home away from home) or working in the lab with research assistants Nate Ralph and JC Weber, she relaxes by paddling the quiet backwaters of the Cape and communing with the warty residents of her woodland frog pond.

Author Maureen Conte prepares to inject the extracted lipids of a trap sample into a capillary gas chromatograph. This instrument is used to separate and quantify up to a hundred different compounds present in a single complex mixture.