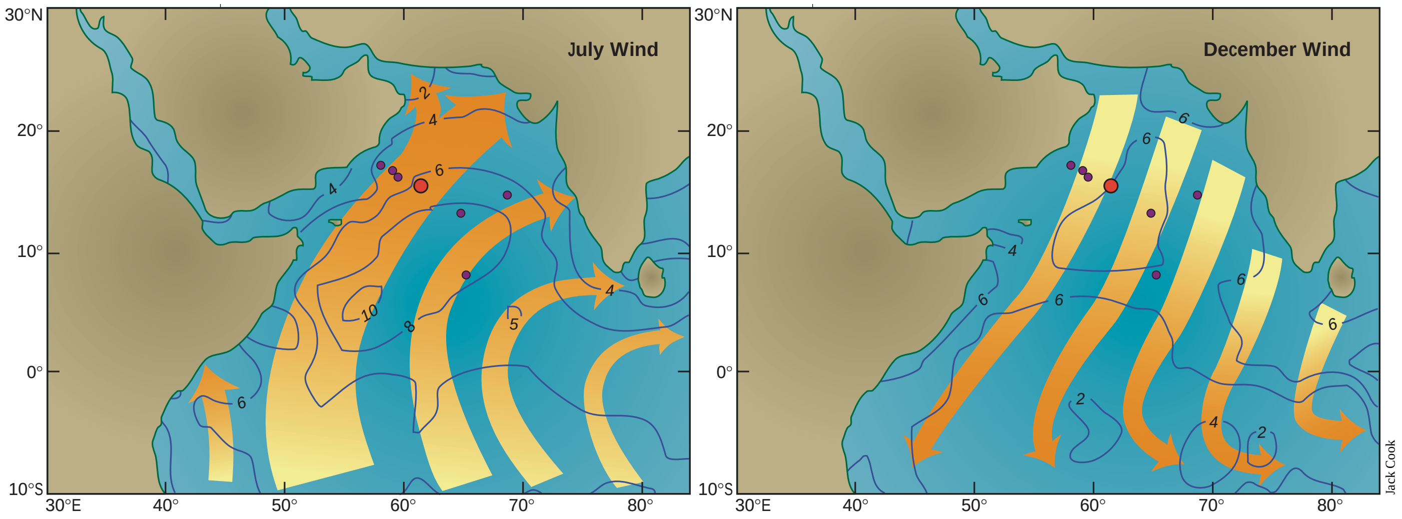

The surface winds and ocean mixed layer depths in the Arabian Sea in July (left) and December (right). The depth of the mixed layer, the upper layer that is well-stirred by surface forcing, is shown in meters. The strong surface winds of the Southwest Monsoon are evident in July, and the moderate winds typical of the Northwest Monsoon blow in December. The locations of the surface Air-Sea Interaction (ASI) and sediment trap moorings are marked by red and dark blue dots respectively.

Monsoon Winds and Carbon Cycles in the Arabian Sea

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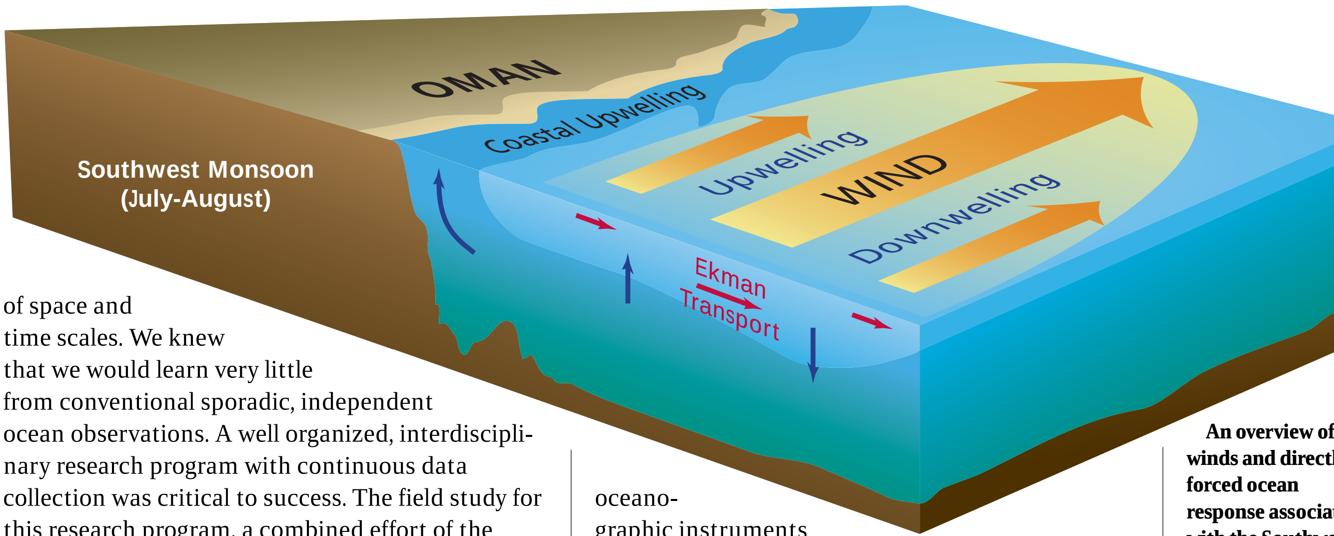
The monsoon, a giant sea breeze between the Asian massif and the Indian Ocean, is one of the most significant natural phenomena that influences the everyday life of more than 60 percent of the world's population. In summer, heating of the land produces a region of intense low surface pressure over northwestern India, Pakistan, and northern Arabia. A broad region of southwesterly winds develops, quite different from the northeast trades found in the other oceans at the same latitudes. The elevated east African coastline intensifies the wind near the surface and directs it parallel to the coasts of Somalia, Yemen, and Oman. This strong flow, the Findlater Jet, is remarkable for its steadiness of direction and its strength, which can exceed 36 knots in July. The offshore Ekman transport (see figure opposite) that results gives rise to intense upwelling along the coast, where cold, nutrient-rich water is brought up to the surface, and to convergence and downwelling in the central and eastern part of the Arabian Sea. In response to the Southwest Monsoon and unlike conditions in any other ocean, the surface mixed layer in the central Arabian Sea deepens and cools during the summer. In midwinter, when the Eurasian continent cools, a high pressure region develops on the Tibetan plateau and northeast winds persist over southern Asia and the Arabian Sea. These winds are not as strong as during the summer, but, combined with strong surface cooling, they lead to deepening of the mixed layer in the central and western Arabian Sea together with higher primary production over the entire Arabian Sea. Thus, the winter monsoon brings a second cycle of mixed layer deepening and cooling to the Arabian Sea.

Even at it coolest, however, the surface water of the Arabian Sea is relatively warm, about 25°C in the central Arabian Sea, and the strong sunlight found year-round in low latitudes can support high productivity in the upper ocean. Thus, nutrient availability is the limiting factor, and primary productivity depends largely on mixing processes that can bring nutrient-rich water to the surface from below. The objective of our work in the Arabian Sea was to understand this link between the physics of the ocean's response to the monsoon and the biological and geochemical variability of the Arabian Sea. Our data show that nutrients brought to the surface by mixing drive productivity in the surface layer, which produces particulates that fall from the surface layer into the deep ocean, removing carbon dioxide (CO_2) from the air to that "sink" region.

The task of observing this biological pump is not easy; the ocean is highly variable, with a wide range



Jack Cook

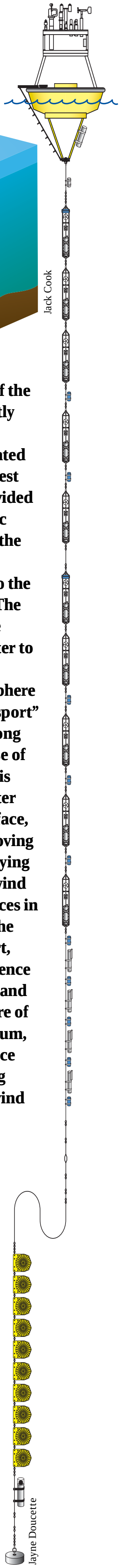
of space and time scales. We knew that we would learn very little from conventional sporadic, independent ocean observations. A well organized, interdisciplinary research program with continuous data collection was critical to success. The field study for this research program, a combined effort of the Joint Global Ocean Flux Study (JGOFS) program and the US Office of Naval Research, began in late 1994 and continued for about one year. It featured observations during all phases of the monsoon, including seven repeated occupations of a cruise track with numerous stops to sample the ocean in detail. In addition, several advanced, moored instrument systems were deployed for the duration to sample the changing Arabian Sea environment continuously, hour-by-hour, at all depths.

In the lull after the summer monsoon of 1994, the Upper Ocean Processes Group of the Woods Hole Oceanographic Institution deployed an advanced surface mooring in the western, central Arabian Sea where the Findlater Jet is strongest. This Air-Sea Interaction (ASI) buoy carried a complete meteorological station as well as an unprecedented number (32) and diversity of oceanographic instruments for measuring temperature, salinity, current, dissolved oxygen, chlorophyll fluorescence, light transmission, and photosynthetically available radiation. This instrument complement resulted from a collaboration of investigators at WHOI, the University of Santa Barbara (Tommy Dickey), and the Lamont-Doherty Earth Observatory (John Marra and Chris Langdon). This buoy was recovered in the spring of 1995 and a fresh set of equipment deployed at the same site until October 1995 in order to collect a full year of data. During the experiment, the meteorological data was telemetered via satellite and published on a World Wide Web site to be immediately accessible by researchers worldwide.

We also deployed in the 4-kilometer-deep ocean a mooring with three time-series sediment traps at depths of 0.8 kilometers, 2.2 kilometers, and 3.5

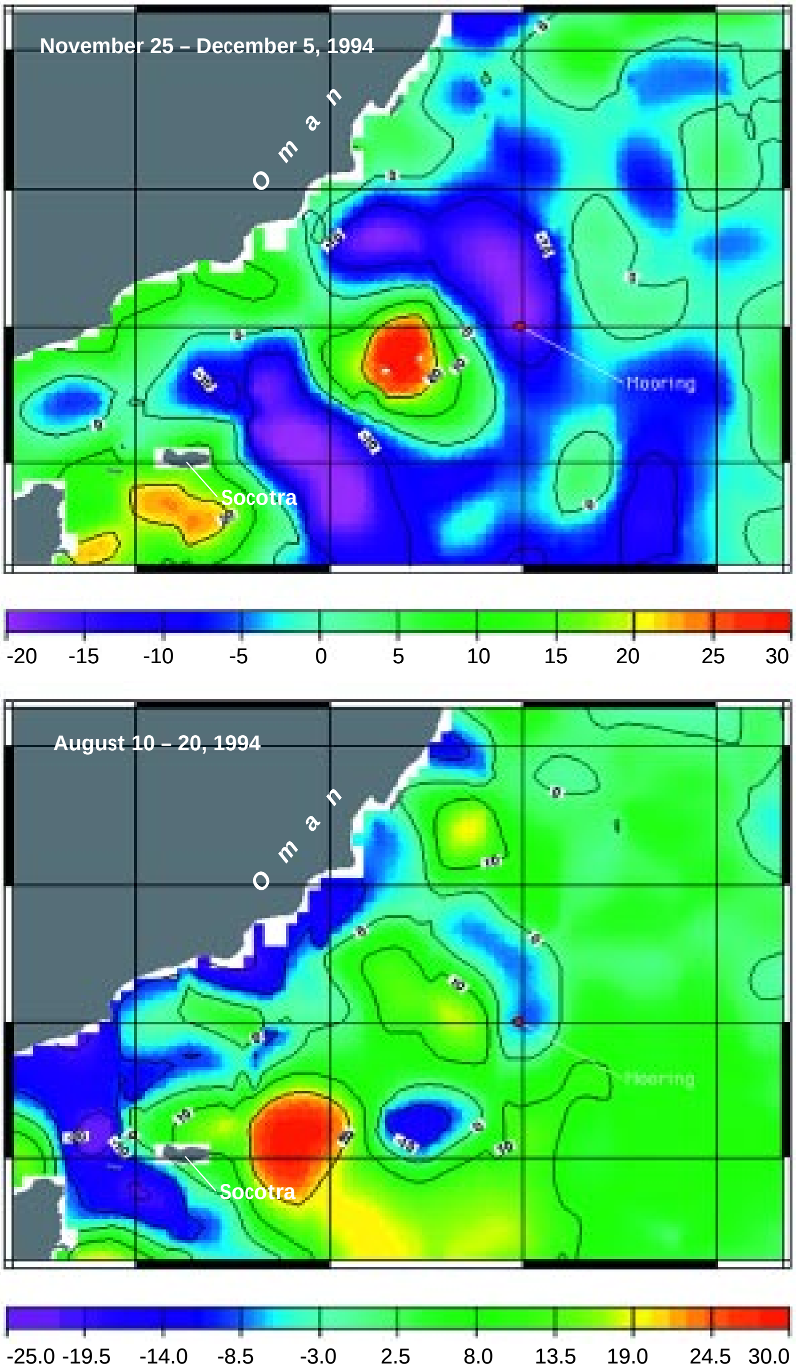
An overview of the winds and directly forced ocean response associated with the Southwest Monsoon is provided by this schematic cross-section of the ocean taken perpendicular to the coast of Oman. The jet of the surface winds drives water to its right in the northern hemisphere as "Ekman transport" (red arrows). Along the coast because of the boundary this leads to cool water rising to the surface, or upwelling. Moving offshore, the varying strength of the wind leads to differences in the strength of the Ekman transport, causing a divergence of surface water and upwelling inshore of the wind maximum, and a convergence and downwelling offshore of the wind maximum (blue arrows).

Robert Weller



Jayne Doucette

The Air-Sea Intraction (ASI) mooring buoy is equipped with two sets of meteorological sensors to measure wind speed and direction, air and sea temperature, incoming shortwave and longwave radiation, barometric pressure, relative humidity, and rain. Current meters and other instruments are located along the mooring line beneath the ASI buoy (see drawing at right). Arabian Sea sediment trap moorings were similar to the drawing on page 9.



Sea surface height, as measured by a satellite altimeter. The height of the sea surface reflects the geostrophic current field associated with large eddies. These eddies form off the Horn of Africa, near the island of Socotra, during the height of the Southwest Monsoon and later drift to the northeast. The strong currents with slowly varying directions seen in May and September in the figure opposite are associated with the passage of these large eddies through the array of moorings.

kilometers. Located about 53 kilometers north of the ASI mooring, these instruments were part of an eight-mooring (24-time-series-sediment-trap) Arabian Sea network fielded by US, German, and Indian scientists during 1994 and 1995. All the sediment traps were set to open and close their collecting bottles at precisely the same time; every eight and a half days a new sample bottle automatically moved into place.

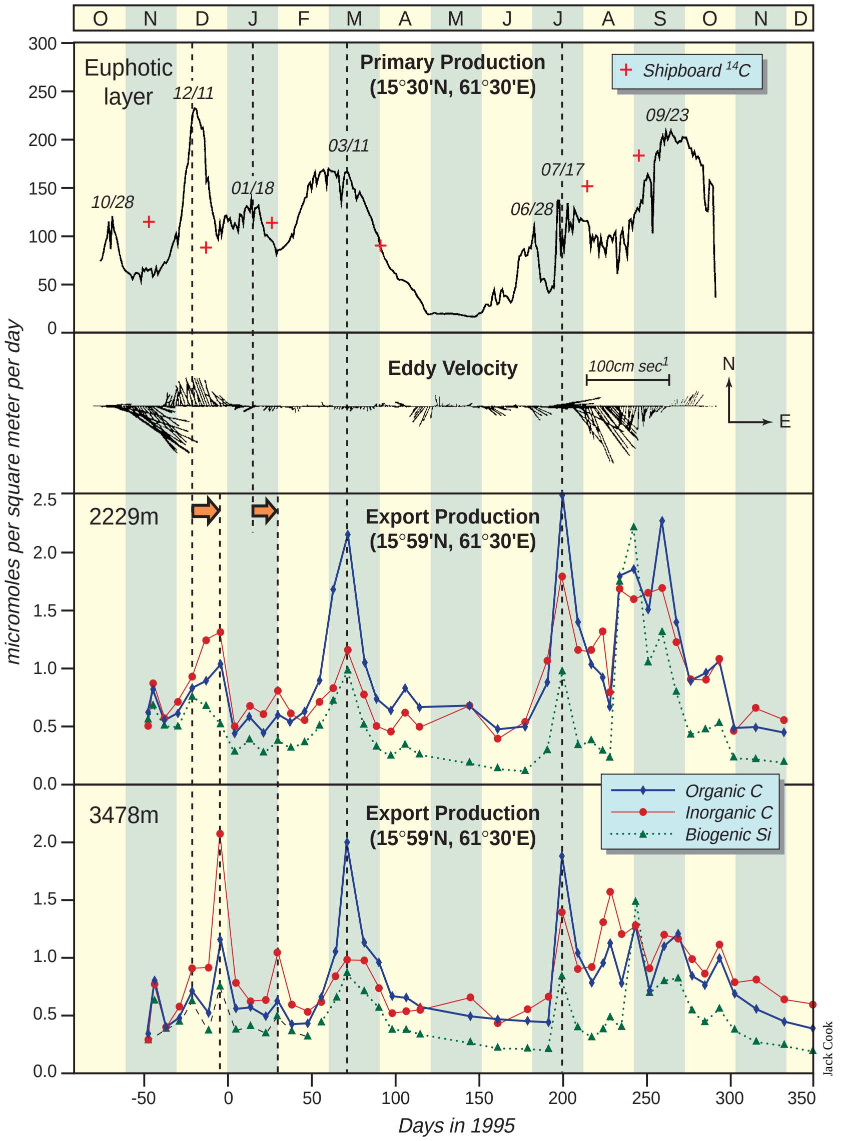
Data from the moorings confirmed our suspicion that productivity in the upper ocean was episodic rather than slowly varying as had been assumed for decades. Tommy Dickey and John Marra's time series of chlorophyll content from their instruments on the ASI mooring showed that most of the annual primary production occurred during four phytoplankton blooms (see figure opposite). Sediment trap data showed that particle flux to the deep interior of the ocean was also strongly episodic—timing as well as relative amplitudes of the increased particle flux closely followed the primary production blooms, offset by several days to a few weeks. In other words, the biological pump in this central Arabian Sea site works hard several times a year rather than operating continuously at a moderate rate. At this location, the biological pump transfers slightly less than one percent of the photosynthetically assimilated organic carbon to the ocean's interior for long-term storage of CO_2 carbon.

These findings have a number of important implications that are applicable to a more general understanding of the ocean. Conventional seagoing productivity measurements in a given ocean area have simply been too scarce to allow us to develop a description of the annual variability in primary production in much of the open ocean. Even the unprecedented, repeated ship survey in the Arabian Sea is hard-pressed to resolve the short, intense blooms seen in the moored time series.

As the figure opposite shows, the day-to-day variability of the primary productivity estimated from Dickey and Marra's instruments coincides strikingly with that of organic and inorganic carbon flux documented by the time series sediment trap array. By comparing the timing of events that occurred in the eupohotic layer with events in the deep ocean layers, we can determine the settling rate of carbon-carrying particles. We previously suspected that the sinking speed of carbon particles falling from the upper ocean is much faster than what had been estimated from Stoke's law, which provides a relation between fall rate and the drag on particles in water. Our Arabian Sea results confirm this important hypothesis about the vertical transport of organic carbon in the ocean's water column. The consequences of the short-lived primary production maximum of December 11, 1994, are evident in the 2.2-and 3.5-kilometer-deep sediment traps, whose sampling period centered on December 29. Settling carbon particles arrived at those depths two 8.5-day sample intervals after the maximum organic carbon production near the surface. However, during the December 7 to 16 open period, the biogenic silica export maximum (mostly from diatom frustules) appeared in the ocean's interior earlier than the organic carbon export maximum. The large organic carbon export event that peaked during the March 11 to 19 open period corresponded to the primary production bloom that peaked on March 11 (though this was not as sharp as the December 11 peak). This indicates that the particulate organic carbon that escaped remineralization reached a depth of 3.5 kilometers within one 8.5-day interval.

During the summer monsoon, the primary production bloom that peaked on July 17 was modest compared to the very large export production event that peaked during the July 17 to 25 sampling interval. A small primary production maximum that peaked on June 28 was not seen clearly in the export flux, but the signal may have blended with the July 17 peak.

The last and largest productivity event of the 1995 summer monsoon began in late August and continued for nearly two months. The organic carbon export production maximum at 2.2 kilometers depth occurred during the September 14 to 22 period, earlier than that of the primary production maximum on September 23.



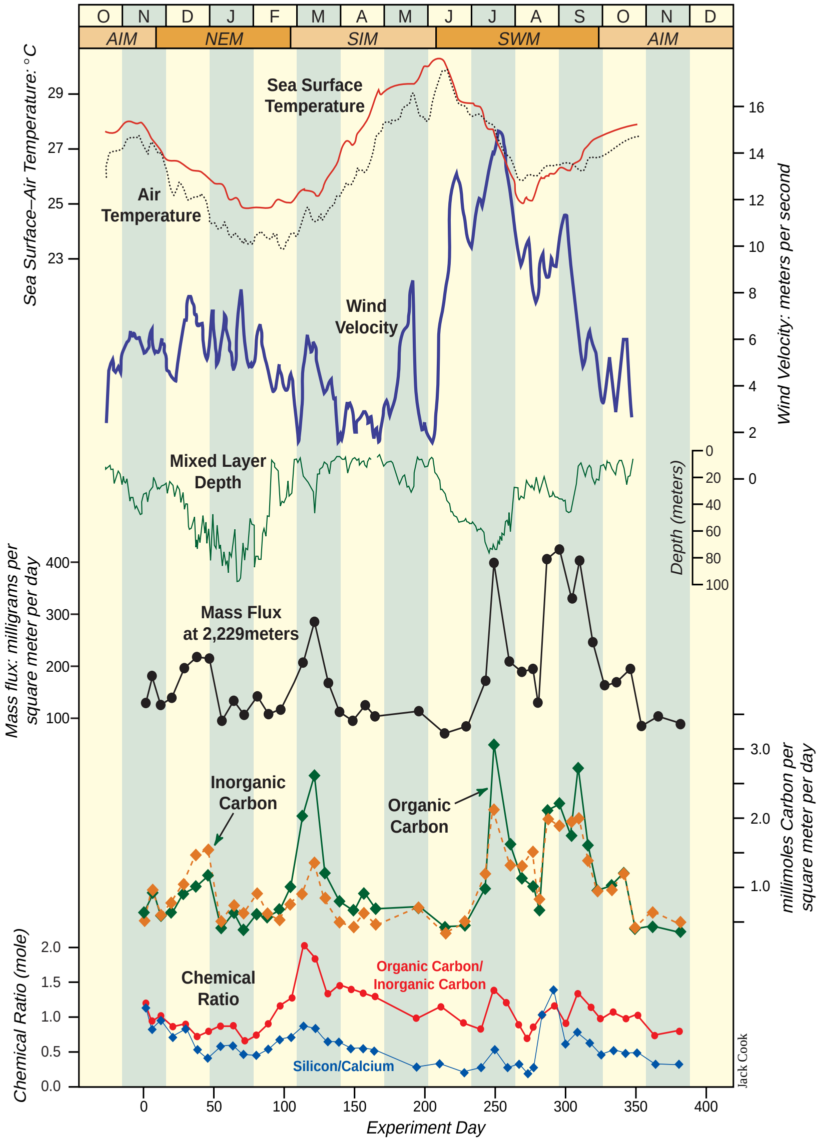
Jack Cook

Time series plots from the surface mooring and nearest sediment trap mooring. Peaks in the variability in primary production (top), based on the measurements on the surface mooring by Dickey and Marra correlate well with peaks in the export production (lower two) measured by the sediment traps at 2,229 and 3,478 meters. Note the correlation as well between the strong currents (second from top) measured by the surface mooring during export production peaks in May and September. These peaks in velocity were associated with the passing eddies.

Thus, we have found the chemical signatures of large bloom events in the euphotic layer to be preserved in exported particles collected in the ocean's interior. The production rate as well as the timing of the bloom is duplicated. Diatom production is a good indicator of the ocean's fertility and the biological pump's efficiency. When conditions that we refer to as "Silica Ocean" prevail, the biological pump functions more efficiently to remove CO_2 carbon from the atmosphere; a Silica Ocean produces more diatoms than coccolithophorids at the initial stage of the biological pumping (see article on page 4). The tropical Arabian Sea is more often a "Carbonate Ocean." However, during the observed periods of high primary production, this sea temporarily becomes a "Silica Ocean," resulting in transport of more CO_2 carbon to the deep ocean sink.

Various physical processes may be involved in the biological pump. Priming the pump requires that nutrient rich water from below the surface layer be brought up into the euphotic region. Near the coast, upwelling does this. In the central Arabian Sea, the mixed layer deepens and cools primarily due to wind-driven entrainment of cooler, nutrient rich water across its base in the summer monsoon. In the winter monsoon, the surface water in the central Arabian Sea is made more dense (cooler and saltier) by surface cooling and evaporation. The dense water sinks and the layer deepens with only modest mixing across its base.

However, another finding of this work leads us to consider different physical processes as well. That finding stems from our observations that the abundance of biologically assimilated silica relative to the calcium carbonate material collected in the sediment traps varies. In practice, we often use the ratio of biologic calcium to silicon found in the flux and/or the ratio of organic carbon (from settling cell material) to inorganic carbon (from settling biogenic calcium carbonate) to quantify this ratio. We observe that the silicon to calcium ratio in the particles exported to the ocean's interior in blooms in December 1994 and August 1995 was very high



Time series plots from the surface mooring and the 2,229 meter sediment trap. The sea surface and air temperature (upper plot) show the cooling that occurs during both the northeast monsoon and the southwest monsoon. The modest winds of the northeast monsoon together with loss of heat from the ocean to the atmosphere lead to deepening of the mixed layer (third plot down) in December and January. The deepening of the mixed layer in June and July during the southwest monsoon results from mixing driven by the very strong winds. The mass flux and carbon flux time series (fourth and fifth down) track the export production seen in the figure on page 27. Time series of the ratios of chemical species in the 2,229 meter trap, organic to inorganic carbon and silicon to calcium, and of the flux of inorganic and organic carbon (bottom) indicate that the chemical signatures vary with wind velocity (positive relationship) and mixed layer depth (negative relationship). The authors are intrigued by the variability and the possibility of linking it to the physics of the mixing that brings nutrients to the surface.

and that during these periods eddies were passing the mooring site. One apparent impact of these eddies is the introduction of nutrient rich water into the surface layer. The strong surface currents associated with these eddies were seen by the current meters on the ASI mooring. The eddies also have a sea surface elevation signature, and Tommy Dickey was able to correlate the passage of particular large eddies observed by satellite with the blooms he and Marra observed at the ASI mooring.

In the euphotic layer of the Arabian Sea, dissolved silica is depleted by the demands of organisms living in the upper ocean layers. As soon as the dissolved silica is supplied from deeper layers to the euphotic layer, diatom production accelerates. In the Arabian Sea, production of coccolithorphorids also increases, but diatom production dominates. The primary production blooms of February–March and July 1995 were not linked to eddies, but were locked to the end of the periods of mixed layer deepening associated with each monsoon. There is also evidence that a dust storm caused by the strong winds in July 1995 covered the entire western and central Arabian Sea coincident with the July bloom. The ratio of organic carbon to inorganic carbon stood out from the background; but while the silicon to calcium ratio in the particles arriving at the ocean's interior during these blooms was high, it was not as elevated as that seen during the eddy-related blooms.

Thus, perhaps one of our most intriguing results is that the chemical composition of what we find to be the rapid export flux from the surface layer may guide our efforts to understand the physics of the Arabian Sea. Convective deepening and wind-driven entrainment appear to result in only modest transport of nutrient-rich water into the surface layer compared to the eddy-related transport. We will now have to consider more carefully the role of eddies. By doing so we will build our understanding of how the biological pump now functions and be able to apply that understanding to the record of how the pump functioned in the geological past as revealed in the records provided by the ocean sediments (see Paleoclimate article on page 11).

Sus Honjo's work was supported by the National Science Foundation, and Bob Weller's by the Office of Naval Research. The data and other contributions to their understanding provided by colleagues, particularly Tommy Dickey and John Marra, is gratefully acknowledged.

Sus Honjo's biography may be found on page 7.

Bob Weller is part of the Physical Oceanography Department's Upper Ocean Processes Group. The talent and skill of this group's technical staff have made it possible to deploy heavily instrumented surface moorings around the globe and to make significant progress toward understanding the interaction of the ocean and atmosphere. His most recent experimental project deployed two surface moorings in the eastern tropical Pacific as part of the Pan American Climate Study. In 1997, this put Bob and the rest of the group at sea and away from WHOI for six weeks in April and May on a Lima, Peru, to San Diego cruise aboard Roger Revelle *(Scripps Institution of Oceanography) and again for six weeks in November and December on a Honolulu to Honolulu voyage on* Thomas Thompson *(University of Washington).*