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Final Report

Carbon Transport in the Bottom Boundary Layer

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Carbon Transport in Continental Margins

I. Abstract

This report summarizes the activities and findings from a field experiment devised to estimate the rates and mechanisms of transport of carbon across the continental shelves. The specific site chosen for the experiment was the Mid-Atlantic Bight, a region off the North Carolina coast. The experiment involved a large contingent of scientists from many institutions. The specific component of the program that was addressed by the research reported herein, was the transport of carbon in the bottom boundary layer. The postulate mechanisms of transport of carbon in the bottom boundary layer are: resuspension and advection, downward deposition, and accumulation. The high turbulence levels in the bottom boundary layer require the understanding of the coupling between turbulence and bottom sediments. The specific issues addressed in the work reported here were: (a) what is the sediment response to forcing by currents and waves; (b) what is the turbulence climate in the bottom boundary layer at this site; and (c) what is the rate at which settling leads to carbon sequestering in bottom sediments at offshore sites. The sediment response to forcing by turbulence was investigated by the author; the turbulence climate was investigated by Dr. Tom Gross of the Skidaway Institute of Oceanography in Savannah, Georgia; and natural deposition was investigated by Dr. Ian Walsh of Texas A & M University (currently at Oregon State University, Corvallis). The data and findings of all three investigators are included in this report.

II. Introduction

The transport of carbon across the continental margins may be a significant part of the overall carbon budget of the earth climate system. At the time of the conception of this program, and indeed even today, it is not clear whether the transport occurs offshore or inshore across these margins. Large-scale motions, and smaller scale bottom boundary layer processes combine to produce a complex matrix of interacting processes, the sum of which produces transport in either direction depending on time and the prevalent forcing by wind, waves, tides, fluvial inputs etc. In addition, CO₂ uptake and oxygen exchange at the ocean surface synthesize organic matter – phytoplankton which set a boundary condition on the surface. The surface and ocean interior processes were examined by a group of scientists from various disciplines. Bottom processes are strongly governed by the development of a boundary layer. It is these processes that the present Grant was concerned with.

The underlying physics of the bottom boundary layer has been explored in great detail in a fundamental way in a series of experiments on both coasts of the US in the past 2 decades. Several experiments, HEBBLE, CODE, STRESS and STRATAFORM have produced much of our current understanding of deep ocean and shelf bottom boundary layer (BBL) processes. In a first-order description of the BBL, a geostrophic flow above it and surface gravity waves force the motions in the BBL. Weaker, but often significant forcing may be contributed by internal waves. The resulting currents decrease in a reasonable well understood manner to zero at the seabed. The shear in the BBL is accompanied by the production of turbulence which maintains the resuspended particles in the water column. The vigor of the turbulence is determined by the interaction of the slowly varying currents and the oscillatory motion induced by waves. The strongest shear occurs at the seabed itself, where also the stress exerted on the bottom sediments is felt. Sediments may be resuspended as a result, or in the absence of strong enough forcing, the

sediments may fall under gravity, be accumulated and compacted, preparing for a subsequent resuspension event.

Models of the dynamics of the bottom boundary layer have been numerous; these are surveyed in an excellent synthesis by [Wiberg, 1995 #1076]. Notable among the models are those by Grant and Madsen [Grant, 1986 #391], and [Sleath, 1991 #94]. The models do an adequate job of computing the velocity field in the BBL. However, the description of the sediment distribution in the BBL requires the specification of the bottom boundary condition at the seabed. This condition describes the relationship between the hydrodynamics (i.e. bottom stress) and the bottom sediment properties, i.e. either a flux or a 'reference concentration'.

The relationship between the exerted bottom stress and the sediment 'response' via a reference concentration is well established in the literature. The original proponent of this relationship was J.D. Smith [Smith, 1977 #915]. However, this relationship involves the use of an empirical constant, the resuspension parameter γ_0 the magnitude of which has been the subject of controversy. The controversy arises not only due to the complexity of the quantification of a natural property of the sediments which bears no simple relation between composition and physical strength, but also because the previous measurements of the reference concentration have been made by poorly conceived, fundamentally inaccurate sensors.

To address precisely this issue, in conjunction with the need to characterize the turbulence climate and events in the MARGINS field experiment area, that we proposed the use of a newly conceived instrument, the MSCAT (Miniature Scattering and Transmissometry). Turbulence would be measured by Dr. Tom Gross of Skidaway Institute using the well-established BASS sensors. At the same time, the size-resolved concentration of sediments would be measured with the MSCAT instrument. The two measurements, respectively, bottom stress and the reference concentration, would then be examined in the context of Smith's formulation, presumably to narrow the range of uncertainty in the magnitude of the resuspension parameter γ_0 .

In addition to the above mentioned measurements, an additional component was added to measure the flux of particles to the seafloor in the form of marine aggregates, also called marine snow. These fluffy, low density, high-porosity particles fall to the ocean floor in deeper waters where the natural turbulence is not vigorous enough to counter gravitational settling. It is postulated that the mass tied up in these particles is quite substantial and may indeed, be the dominant component in the suspended particulate mass in low-turbulence regions. Dr. Walsh's sediment traps would make the measurement of these aggregates. The combined suite of instruments was designed to produce a comprehensive set of flux estimates that would then be integrated to produce an answer to the question: Does carbon move onshore or offshore in the BBL at the Mid-Atlantic Bight.

III. Experimental Methods

In this write-up, we describe the measurements of the sediment reference concentration only. The separate write-ups by subcontractors Drs. Walsh and Gross describe the results obtained in their components in Appendix I and II.

The underlying technology for measurement of the reference concentration is laser multi-angle scattering. Also called laser diffraction, this method is based on the observation of laser light scattered at several angles in the small-angle forward direction. The advantage of this concept is that it is relatively insensitive to particle composition (i.e. refractive index) and therefore is suitable for a broad range of applications even where the composition of particles is not known.

In figure 1, we describe the basic principles. A laser beam, derived from a semiconductor laser diode, and collimated by an achromatic doublet, enters water. A coaxial receiving lens receives light scattered by particles. A specially constructed detector, which has 32 concentric rings centered on the optical laser-axis, receives the scattered light. Each ring represents a range of scattering angles. The ring inner radii increase logarithmically as also do their widths. The relationship between the scattered light energy sensed by these ring detectors, $\underline{E}$, is related to the size distribution $\underline{N}_A$ via the scattering property of the particles embodied in the kernel $\underline{K}$ as follows:

$$\underline{E} = \underline{K} * \underline{N}_A$$

where the area distribution is defined as $a^2n(a)$ and a is the radius of a particle. The area distribution is obtained by inverting the 32-element observation vector $\underline{E}$. From the area distribution, the volume distribution is obtained by multiplication with the radii corresponding to the 32 size classes.

Figure 1: The basic optics of the small-angle scattering method for measuring size distribution of an ensemble of particles. The sketch (lower left) illustrates the signature of particle size: small particles scatter into larger rings and vice versa. The ring detector is shown in lower right. A central hole in the ring detector permits the measurement of laser transmission which is used for correcting for attenuation of scattered light.

The physical manifestation of the instrument appears in figure 2. The sensing head alone is shown in this figure. The electronics, data storage computer and batteries are placed a small distance away, in a pressure housing. Contained in this housing is the laser light source. A single-mode optical fiber delivers the light from this laser to the sensor head. The light emerging from the fiber is collimated and folded by an external right-angle prism. The space between the two prisms is the sample volume. Particles in this sample volume produce the scattering signal that is sensed by the multi-ring photo-diode array placed behind the focusing lens. The photocurrents from these rings are amplified, digitized and stored on the on-board computer in the pressure housing.

Figure 2: The sensor head details.

The instrument itself was mounted, along with a common particle size distribution-sensing instrument, the LISST-100, on a tripod.

Figure 3: The MSCAT instrument is shown along with a LISST-100 and LISST-ST mounted on a tripod used in the Margins experiment. The MSCAT sensor head is hanging from the central column. The LISST-ST was used for the measurement of the settling velocity distribution.

IV. Results

The tripod shown in figure 3 above was deployed in the Mid-Atlantic Bight on two separate occasions. The sampling schedule for the MSCAT was to acquire 128 scans at 1Hz, every 6 hours. In this manner, any wave-modulation of the reference concentration would be examined. The deployments lasted over a month each time, and at the end of each deployment, instrument degradation due to optical fouling was observed.

fig. 11

fig. 12

In figure 4, we show key results obtained using the instrument suite. We show the size distribution during a typical 128 second data event. There is a suggestion that the large size particles are intermittent. Whether this intermittency is due to wave-induced oscillation or due to the natural randomness due to small number statistics was examined separately as follows.

Velocity data from the BASS sensors was identified that synchronized with the time of the particle data above. The speed vs. total sediment concentration is examined and displayed in the lower plot. A clear correlation was not found.

V. *Concluding Remarks*

A suite of instruments was deployed to examine the dynamics of the bottom boundary layer and in particular, the reference concentration. While the details of the data remain to be examined in the course of a possible future grant, initial indications are that at the distances at which the reference concentration was measured, no direct correlation between wave forcing and the suspended concentration was visible.

There remain several tasks related to this data. First and foremost, is the task of relating the bottom stress estimates to the measured reference concentrations, so that the parameterization of the resuspension parameter is reviewed and expanded on a size-specific basis. Second, the long-term variability of the reference concentration and the robustness of the relationship.

The details of the bottom boundary layer velocity field are reported by Dr. Gross in Appendix I. The conclusions from the work at the offshore site are reported in the Appendix II.

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