Benthic “Weather” Current Meter Array

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Abstract – **An array of deep ocean current meters capable of resolving Reynolds stress, deployed on 10 km grid spacing over an area 100 km x 100 km, can resolve benthic storms responsible for eroding and transporting sediment. The requirement for such an array is that the current meters be inexpensive yet capable of obtaining stress measurements. A design for both instrument and array must include power, logging, and noise considerations; recovery of instruments and/or data; and economics and logistics of deployment. A version of the Modular Acoustic Velocity Sensor, MAVS, is to be adapted to this task.**

I. Introduction

A. Spatial and Temporal Coverage

Until 1950, scientists observed the physical ocean with spot measurements at single geographical positions and depths and at single instants in time. In the next decade, moored instruments extended the time series of observations at a single depth to months, then years. Moored profilers, like the ADCP in the last decade, have extended the observations to continuous depth profiles over time. Autonomous underwater vehicles promise to provide observations along horizontal tracks, repeated periodically over extended time. But there has been no quantum leap that enables continuous horizontal coverage in two dimensions over extended time below the surface. To extend observations horizontally in two dimensions and have a continuous time series is now dependent on inexpensive sensors that can be deployed in an array and that will measure and record continuously.

Weather observations in the atmosphere typically benefit from such horizontal coverage with continuous or periodic sampling. Fluid processes require horizontal arrays or imaging to capture their spatial structure, weather being an example of such a process. Even in the ocean, important processes require resolution of structure for their understanding. Deep convection, Langmuir circulation, breaking internal waves, solitons, and fronts are all incompletely observed with a time series at a single location or a profile at a single time. Even a section, continuous profiles along a horizontal line, misses many features of such fluid processes. But episodic events such as storms are still more difficult to capture without an extended time series and then the spatial coverage is typically absent.

B. High-Energy Benthic-Boundary Layer Experiment

From 1979 through 1987, currents, optical transmission, and sediment transport were studied at 4800 meters on the Nova Scotia continental rise [1]. We restricted our measurements to a 2 km x 4 km rectangle and put enough instruments in this area to show that the boundary layer was one dimensional. There were essentially no horizontal gradients; everything could be described as a function of height above bottom. However the temporal history was rich. Erosional events were rare. Most turbidity events were advective [2]. Yet there were no significant horizontal gradients over 4 km. One is forced to recognize that erosional storms are local and infrequent but that their influence is dominant for sediment transport on the lower rise (a region encompassing several percent of the earth). Topographic constraints suggest that a cross rise array of 100-km width should have captured such a storm passage. Since advective events were observed every 10 days or so, several passages per month might be expected. Near-erosional events were also observed at HEBBLE at intervals of a few months. The suggestion was that increasing shear stress resulting from increasing current speed approached the threshold for erosion but exceeded it at some other location, possibly upstream but possibly in some other direction. In any case, the intermittence of stress sufficient to erode sediment implies that even a cross rise array would rarely capture an erosional event. In fact, the structure of a storm is so poorly envisioned that we can’t guess where sensors should be placed to observe local erosion. The bigger question is the nature of critical fluid events, let us say images of benthic “weather”. What is the evolution of isotachs over a region 100 km x 100 km during a three month period?

II. Instrumentation

A. Requirements of a Benthic Weather Current Meter

Based upon HEBBLE, the critical observations of the benthic boundary layer at a single location are current speed, current direction, bottom stress, sediment concentration, and water mass properties. Current speed and direction are necessary for transport and are primitive physical observables. Bottom stress is the critical fluid quantity responsible for erosion of sediment and is not simply related to current speed because bottom roughness and turbulent boundary layer evolution are involved. Traditionally, bottom stress is rarely measured at a point on the bottom. A shear stress measurement at a point on the bottom is both difficult and particular (not representative). Some spatial averaging is desirable to get a representative stress and the two methods used are a log current speed profile and a local turbulence correlation.

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Suspended sediment concentration is the result of exceedance of the fluid stress over the strength of the sediment integrated over time and over advective distance less deposition and vertical diffusion. It is complicated to measure and complicated to interpret. For the purpose of imaging benthic weather events, a qualitative measure of changes in sediment concentration provide horizontal gradients that suggest erosion or deposition. Optical turbidity, as measured by an optical back scatter sensor (OBS) gives such a signal and is relatively easy to measure.

Fluid moves as the result of pressure gradients and inertia but water of diverse origins carries dynamically significant properties, principally density, and interesting but dynamically insignificant properties such as very fine sediment concentrations (nepheloid characteristics). The dominant signal that is dynamically significant in the deep-sea is temperature. Salinity has a smaller variation and the differences in salinity between deep-sea water masses are often not detectable. Antarctic bottom water at the HEBBLE site, a possible foreign water mass, was only distinguishable from Labrador Sea water in silicate, a much more difficult property to detect.

B. Reynolds Stress Considerations

Bottom stress results when shear in the bottom boundary layer generates turbulent eddies that advect high velocity fluid toward the bottom and low velocity fluid away from the bottom. This turbulent exchange of momentum represents a stress. The individual eddies are locally diverse and the stress is stationary only when averaged horizontally over a considerable area. It is also horizontally homogeneous only when the bottom is flat and uniform. In practice, the horizontal average is easy for the fluid to do but hard for the instrument to measure and the ergodic hypothesis is invoked to allow a time series average at a point to replace the spatial average. The time must be short enough to assume stationarity and long enough to achieve stability, typically 30 minutes in the deep-sea. Over a region called the inertial sublayer, the stress is constant. This is the region bracketed by the viscous boundary layer (or the actual surface roughness) at the smallest distance from the bottom and by the outer layer (the penetration to which the last acceleration in flow has established equilibrium) at the largest distance from the bottom. Were the stress not constant, there would be acceleration and the boundary layer would not be steady.

The alternative to measuring the stress at one position is to measure the profile of velocity across the constant stress layer and fit the speed to the logarithm of height. The slope is proportional to stress and the intercept to roughness. It is not sufficient that there be a logarithmic fit of velocity since the speed profile may be a relic of a previous boundary layer upstream with a different stress. Also it requires more sensors to measure velocity at several heights than to measure Reynolds stress at one height. So the logarithmic profile method to estimate bottom stress is really less attractive than the measurement of Reynolds stress or of turbulent kinetic energy at a single height within the constant stress layer. 1.5 meter above the bottom is a good height for such a measurement in the deep-sea.

To estimate Reynolds stress, measure 3-D vector velocity over a volume small compared to the distance from the boundary, correlate the downstream and vertical components of flow, sample at a rate fast enough to prevent aliasing with the sensing volume and the advective velocity expected, and average for an interval short enough to satisfy stationarity and long enough to achieve stability. In previous Reynolds stress measurements in the deep-sea (tides and internal waves but no surface waves) four components of velocity were sampled at 2 Hz and the self-product and the cross products of all four components were accumulated [3]. The means of the four components of velocity and the means of the accumulated products were stored every 30 minutes. The self-products provided three axes of turbulent kinetic energy, the cross products gave Reynolds stress, and the means gave the advective speed and direction.

Correlated components and means can be stored compactly. Including time stamp, orientation information, temperature, and turbidity, the record is less than 50 bytes. At a record every 30 minutes, more than 2 years of measurements could be stored in 2 megabytes of memory. Thus, the Reynolds stress technique for observing benthic weather is lean.

In the deep sea the leakage from waves into the Reynolds stress correlations, resulting from unresolved tilt of the instrument, is not a problem. On the shelf and near the shore, waves complicate the estimate of Reynolds stress and the dissipation method of estimating stress is preferred [4]. Velocity sensors separated horizontally by several times their height above the bottom, yet still within the constant stress layer, sample the same wave velocity but uncorrelated turbulence. Differencing these measurements removes waves but retains turbulence. This difference can be used to estimate bottom stress. Horizontally separated sensors are not cheap to deploy. A second technique for determining turbulent kinetic energy with waves is to spectrally isolate the wave band and estimate a turbulence level from a –5/3 inertial subrange fit to the remainder of the spectrum of velocity. Unfortunately, this does not separate cleanly and the technique is still being explored [5]. Spectral data can also be compactly stored if a block of samples are Fourier transformed every 30 minutes and only band averages are saved.

C. Power

Three months of observation is required to have a high probability of capturing a benthic storm. This length of deployment with a battery pack of 280 watt-hours (20 inches of case length) requires an average current of 8 ma from a 15-cell alkaline battery. This is a reasonable target based upon past experience with BASS [3] where the average power for continuous 2 Hz samples at five sensors consumed 12 ma from a 6-cell lithium battery. The power use breakdown is distributed between measurement circuitry, CPU/memory cycles, and switching regulator metabolism. The acoustic measurement with MAVS requires 15 millijoule per measurement. At 2 Hz, this is 70 watt-hours for the deployment. Using a Tattletale 4A processor (Onset Computer Corp., Bourne, MA), the active computation mode requires 10 ma, the standby mode requires 2.4 ma, and the shut down mode reduces the current drain to 30 µa. The switching regulator that converts the battery voltage (23 volts when the battery is fresh to 14 volts at end of life) to regulated 12 volts has a metabolism of 70 mw or 5 ma at end of battery life. These numbers show that the CPU and the switching regulator must be shut down between measurements.

D. Noise Considerations

Current measurements are affected by noise of three types. These are electronic noise, flow distortion, and fluid wake. For determination of Reynolds stress, variance and bias are both of concern but bias is only serious if the sensor is not fixed. Electronic noise adds variance to the measurement, which becomes a limit at low velocities. Drift, a kind of electronic noise, acts to introduce a zero offset that is not the same at the beginning of a deployment and at the end. It may be discontinuous, as from a strain on a component of the sensor that is relieved, or it may be gradual as from aging of a plastic part that affects capacitance. In some cases the offset from the first can be corrected but in the second case little can be done precisely. Errors of electronic origin are offset errors or noise floors below which true velocity fluctuations cannot be measured.

Flow distortion caused by structure of the sensor affects the measured speed as a function of orientation. What is of greater consequence for the Reynolds stress measurement is its affect on the apparent direction of instantaneous flow. Flow distortion of a sensor is summarized by the horizontal and vertical cosine response, the deviation the actual vector components have from speed times the cosine of the angle between the undisturbed flow and the component direction. The error due to imperfect cosine response is proportional to speed. It is a function of orientation.

Fluid wake has two effects. The first is the velocity defect in the wake generated by structural elements in the sensor. The defect varies directly with the diameter of the structural elements and inversely with the distance to the elements. It is an error proportional to speed. The second effect is the turbulence generated by vortices shed by structural elements. This is potentially a more serious problem for measuring Reynolds stress since these vortices may produce correlations. Structural vortices are true Reynolds stress contributors but are not those one wishes to measure. Vortices from structures are fairly narrow band features of the wave number spectrum.

How bad can the noise be and still permit us to measure stress well enough? The Reynolds stress at the HEBBLE site was typically 1 dyne/cm^2 with a mean current of 30 cm/s at 1.5 meter above bottom. This represents rms fluctuations of 3% of the flow. At 10 cm/s mean flow, there may be a boundary layer observable at 1.5 meter above the bottom. So that sets the noise floor requirement which at 3% of the flow is 3 mm/s. Fluctuations in flow should be easily measurable at the 3% level or 3 mm/s, whichever is greater. So a target for the noise might be set at 1% of the flow or 1 mm/s, whichever is greater.

How bad can the flow distortion be and still get Reynolds stress? Fluctuations in downstream velocity at the 30% level are present in the turbulent boundary layer flow [1]. Distortion of these downstream fluctuations into the vertical at the 3% level would contaminate the Reynolds stress 100%. This error is produced with a vertical cosine response error of 5.7˚. To ensure that the distortion of fluctuations in downstream velocity accounted for only 2% of the observed vertical fluctuations requires that the distortion be only 4˚. Since the vertical cosine response is orientation dependent, it is probably sufficient that the limit of 4˚ be required over the expected instantaneous flow direction, generally within 20˚ of horizontal.

How bad can turbulent fluctuations in the wake of structures be and still measure stress? The correlated contributions of the wakes to the measurements should be below 1% of the flow to avoid serious contamination of the Reynolds stress measurement. Uncorrelated wake contributions might possibly be higher since the Reynolds stress averaging removes zero-mean uncorrelated quantities. If one assumes 1/3 of the fluctuations in the wake correlate (downstream with vertical) then the limit for rms flow noise in the wake is about 3% of the flow velocity. Without actual measurement this assumption is hard to support but if it is accepted subject to experimental verification, the Modular Acoustic Velocity sensor, MAVS, does meet the noise criteria for measuring Reynolds stress. The rms flow noise is 1.5% at 40 cm/s and is 2.5% at 80 cm/s. Electronic noise is equivalent to 0.5 mm/s rms flow noise. The deviation from ideal vertical cosine response at 15˚ elevation is 5% or 2.8˚ [6].

III. Observational Program

Development of MAVS was initially motivated by the desire to measure benthic weather in the HEBBLE region. Sediment came to the array from somewhere upstream but there were no observations upstream. Many instruments on nearly as many moorings are required to address this measurement task. The economics of this many moorings (and this many instruments) requires a level of cost consciousness rarely exhibited in ocean research. The cost of the instruments has to be low (therefore a mass produced sensor is recommended) and the cost of the moorings has to be low (thus expendable techniques are worth exploring). Deployment and recovery costs are critical. Testing and development costs are less critical because the number of sensors and moorings is so large that development costs can be spread over many units.

A. Recovery of Data

Consider the array containing 100 moorings, each with a single instrument. Each instrument can contain 2 megabytes of data. In a three month deployment, 30 minute averages only amount to 216 kilobytes but the excess capacity can contain raw measurements before averaging. How can these data be recovered? The conventional answer is to recover the moorings and take the data off on deck. Two problems present themselves for this approach: the release of the instruments and the location of the moorings at the surface.

1. Timed Release

The lowest cost in hardware is a timed release. A buoyant mooring with a weight connected to the instrument by an electrically corrodable link can be released on schedule. The benefit of this is that no interaction is required from the ship; the release can occur before the ship is in the mooring area. The difficulty is that a delay in the schedule of the ship or a difficulty in locating a single mooring could jeopardize recovery of the entire remaining array. Also, timed releases are notoriously vulnerable to bad weather. The relocation of the mooring at the surface is also difficult. If deployment position, expected or measured current, and time to the surface are computed, the uncertainty of location at the surface may well be several hundred meters and once the mooring reaches the surface, the uncertainty increases rapidly. The visual target is small and vision is not reliable in poor weather or at night. So losses will be high.

2. Acoustic Command Release

Time constraints are relaxed if mooring release is commanded from the surface. Acoustic command can be incorporated with modest increase in hardware cost. The benefit is largely in allowing bad weather or ship schedule changes to be accommodated. The difficulty in relocation is still present. The more serious cost may be the added ship time that is spent waiting for the mooring to rise from 4800 m to the surface, typically about 2 hours. A small transducer is sufficient to receive acoustic commands. A much larger and more costly transmitter is required to reply to ship commands. However, a transponding release allows the mooring to be tracked to the surface and ensures that the ship is close to the mooring when it comes up. Generally when the transponder is on the surface, acoustic communication is lost so surfacing time is critical.

3. Acoustic Telemetry

The data are more valuable than the instruments unless a post deployment calibration is required. So the expendable instrument with data telemetry should be considered. Acoustic telemetry from the bottom, triggered by acoustic command perhaps, is a possibility. High baud-rate acoustic-telemetry modems (ATMs) are expensive and require significant power and high bandwidth transducers. With such equipment data could be dumped to the ship in less than an hour. Lower power, simpler ATMs, could dump data in several hours. But there is a trade off between instrument complexity and cost and speed of data transmission.

4. Satellite Telemetry

Timed release followed by satellite data transmission is an attractive alternative to ship recovery. A ship may not even be required to be assigned. The example of RAFOS drifters [7] and ALACE floats [8] illustrate how Argos satellite return of data is practical. The Argos transmitter is complex but is available and the freedom from need to recover the instrument is attractive. If the instrument had value for a subsequent experiment, it might be recoverable using its Argos transmissions to home (as has been done for other Argos transmitters). The time required to transmit the entire datafile is however substantial since the Argos data rate is low. Based upon RAFOS data telemetry via Argos, 30 days would be required to transmit the 216 kilobyte averages. The remaining 1.8 megabytes of unaveraged data could not be returned by Argos.

B. Deployment in the Deep Sea

The deployment scheme is particularly attractive. A ship steaming at 12 knots covers 10 km every half-hour. A mooring deployed from the ship every half-hour for 2 days will fill a 100-km x 100-km square on 10-km centers. So it is a cheap way to instrument the region. The mooring configuration, shown in Fig. 1, is a weight, release link, Argos antenna, buoyancy module, and MAVS instrument. The sensor is 1.5 meters above the bottom and the region beneath the measurement volume is modest in cross section to minimize the flow disturbance close to the sensor. Slipping a line suspending it close to the sea can launch the mooring. The package can be tied together with low-density polyvinyl alcohol (PVA) film so it withstands the impact of launch but is free upon reaching the bottom.

Measurements will be continuous but samples will be averaged half-hourly and stored in a datafile. Unaveraged samples will be retained in memory but not for transmission.

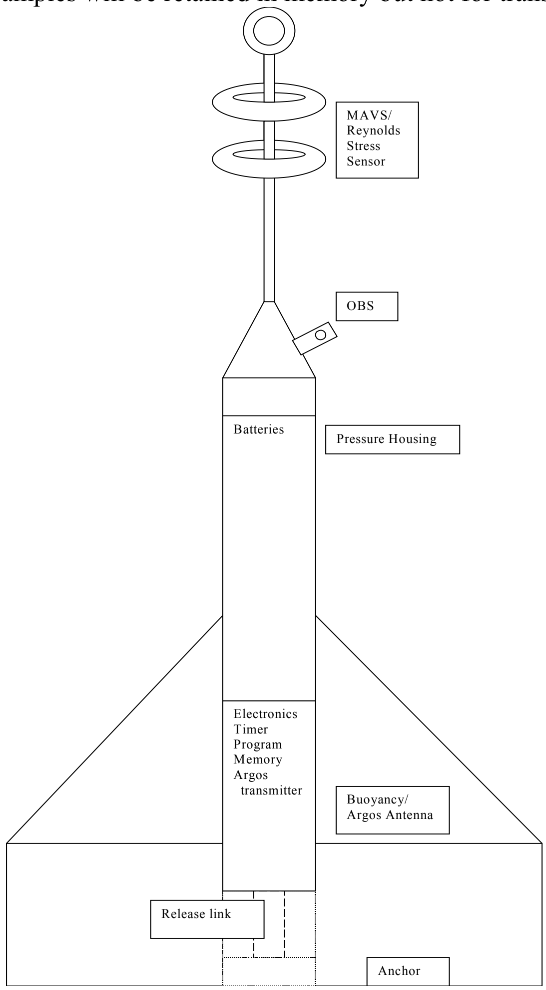

Fig. 1, MAVS with anchor, timed release, float, Argos transmitter, velocity and turbidity sensors, and batteries.

At end of mission, the timer closes the circuit to the corrodable wire release, the link to the anchor weight parts and the instrument inverts and rises to the surface. It also starts transmitting data from the Argos antenna. Argos only passes overhead at twilight so it requires several weeks to dump the averaged data. A ship can pick up the drifting instruments during this period using the Argos positions to get close and the Argos transmissions with a direction finder to home on the instruments. The requirements of data telemetry are so great that it is perhaps most reasonable to consider this only for the instruments that are lost and accept that only a small fraction of the data will be so returned.

Recovery of transmitting floats would require typically several hours per float. If the array releases on a preset schedule, intervals of 2 hours would allow an optimized recovery schedule but there would have to be time at the end of a nominal ten day cruise for hunting down moorings that were lost in the initial sweep. If there were bad weather during the release period, the entire dispersing array would have to be tracked down later.

C. Tests in Shallow Water

Before putting out the entire array in deep water, a test deployment of a reduced array is needed to verify the deployment and recovery schemes, to establish interim development milestones, and to test the data analysis plan. Draggers on the shelf present hazards to array survival but the deployment might be done in a region closed to fishing or might be short in duration. The array should be significantly smaller than the final array, perhaps 16 moorings. A shallow deployment ensures that the floats are close to the deployment position and visual relocation will be more successful. The test need not be high risk to loss.

IV. Summary

An array of Reynolds stress measuring current meters can be built and deployed economically on the lower continental rise to observe benthic weather. The noise levels of MAVS are low enough to resolve the stress responsible for sediment erosion. In situ processing of vector velocity measurements stored at 30-minute intervals for 3 months can be accommodated in a moderate sized instrument that can be deployed from a ship underway. The array can be recovered with a timed release and an Argos satellite transmitter for homing and data return.

References

[1] Gross, T.F., A.J. Williams 3rd, and W.D. Grant, 1986. Long-term in situ calculations of kinetic energy and Reynolds stress in a deep sea boundary layer, J. Geophys. Res., 91, pp. 8461-8646.

[2] Grant, W.D., A.J. Williams 3rd, and T.F. Gross, 1985. A description of the bottom boundary layer at the HEBBLE site: Low frequency forcing, bottom stress and temperature structure, Marine Geology, 66, pp. 219-241.

[3] Williams, A.J. 3rd, J.S. Tochko, R.L. Koehler, W.D. Grant, T.E. Gross, and C.V.R. Dunn, 1987. Measurement of turbulence in the oceanic bottom boundary layer with an acoustic current meter array, J. Atmos. and Oceanic Tech., 4(2), pp. 312-327.

[4] Trowbridge, J.H., 1998. On a technique for measurement of turbulent shear stress in the presence of surface waves, J. Atmos. and Oceanic Tech., 15(2), pp. 290-298.

[5] Gross, T.F., A.J. Williams 3rd, and E.A. Terray, 1994. Bottom boundary layer spectral dissipation estimates in the presence of wave motions, Cont'l. Shelf Res., (10/11), pp. 1239-1256.

[6] Thwaites, F.T., and A.J. Williams 3rd, 1996. Development of a modular acoustic velocity sensor, Oceans 96, pp. 607-612.

[7] Rossby, T., D. Dorson, and J. Fontaine, 1986. The RAFOS system, J. Atmos. and Oceanic Tech., 3, pp. 672-679.

[8] Davis, R.E., D.C. Webb, L.A. Regier, and J. Dufour, 1991. The Autonomous Lagrangian Circulation Explorer (ALACE), J. Atmos. and Oceanic Tech., 9, pp. 264-285.