A Free-Drifting Measurement of Mid-Water Mixing by an Acoustic Current Meter Array in NATRE

Albert J. Williams 3rd

Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Abstract - **A five meter tall array of acoustic travel-time current meters, was deployed in the North Atlantic Tracer Release Experiment in May, 1992, to measure shear and internal wave mixing. Preliminary results from a four day test deployment at the start of the experiment show shear of 2 cm/s over the 5 meter length of the array with much variability.**

I. INTRODUCTION

Mixing in the interior of the ocean, away from boundaries, is thought to occur by internal wave mixing and by double diffusive convection (where temperature or salinity is destabilizing) [1,2]. The North Atlantic Tracer Release Experiment, NATRE, was designed to measure the diapycnal (across density surface) mixing through injection of a tracer (SF_6) on a constant density surface near 300 meters depth in the main thermocline in the eastern Atlantic [3]. Direct measurement of internal wave shear and density gradient over the year long experiment at the location of the tracer was expected to provide an added benefit by revealing at least the internal wave processes responsible for the mixing that would be observed through spreading of the tracer.

1) *Richardson Number:* Overturning can occur in a stratified shear flow when the Richardson number drops and remains below 1/4. This dimensionless number, Ri, is the ratio of stratification to shear squared:

$$Ri=[(g/\rho)(d\rho/dz)]/[(dv/dz)^2]$$

where g is gravitational acceleration, ρ is density, d/dz is vertical gradient, and v is horizontal velocity. At vertical scales of tens of meters, this number is generally larger than 1/4 but at scales of meters, it is sometimes found to approach 1/4. At scales much less than one meter, both the velocity difference and the density difference become so small that the measurement of Ri becomes noisy and difficult to determine. Microstructure profiles suggest that scales of 0.2 meters to 1.0 meters are most likely to exhibit overturning. Straining of the density gradient by internal waves and generation of shear by internal waves affect the instantaneous Richardson number but the growth of an overturning structture requires the Richardson number to remain below 1/4 long enough to wrap fluid lines around a vortex tube of the scale of mixing. If overturning occurs, the inversion of density removes the stable stratification and some fraction of the fluid within the overturn region mixes, the scales of fluid motions and gradients of temperature and salinity cascading to smaller scales until viscosity stops the motion and molecular diffusion removes the gradients at the smallest scales.

Internal waves do not generally break. However, superposition of low frequency inertial oscillations with higher frequency internal waves and possibly a geostrophic mean shear, may bring the shear to the critical Richardson number. Inertial oscillations, forced by changes in surface wind stress, can propagate vertically and ultimately provide the momentum flux that can mix the interior. Thus the possibility that diapycnal mixing is somehow connected to weather deserves testing with long time series measurements of Richardson number in a region where the tracer is injected.

2) *Swallow Float and Bobber:* Tracer injected at very low concentration moves with the fluid, subject only to diffusion and mixing as are temperature and salinity (not counting double diffusion). An instrument matching the density, compressibility and thermal expansion of seawater at the target density surface should similarly move with the tracer. An instrument less compressible than seawater approximately tracks the water at the depth where its density matches that of the water. Such an instrument is a Swallow float. When equipped with a control system to track a surface of constant temperature, a better approximation to the tracer results. An array of Bobbers [4], Swallow floats with buoyancy control and an isotherm tracking program, were deployed in NATRE with the tracer. Each Bobber had a low frequency beacon and precision clock for tracking the float in the SOFAR channel. Two Bobbers were selected to mark and support Richardson number measuring instruments with an anticipated life of a year.

This work was supported by the National Science Foundation and by the Office of Naval Research through the National Science Foundation on Grant No. OCE-9018623. This is WHOI Contribution No. 8453.

3) *RiNo Float:* A free-drifting five meter tall array of acoustic current meters was equipped with additional sensors of density and density gradient so that it could measure the Richardson number. This instrument, first used in 1986, is called a RiNo float [5]. By itself, it has little ability to track an isotherm although it can be commanded to change its volume and thus change its equilibrium depth. Creep of its aluminum pressure cases results in gradual sinking that would soon remove the RiNo float from the target density surface and subduction of the density surface would not be detected until data analysis so that it could lose the target tracer in this way as well. By tethering the RiNo to the Bobber, the target surface could be tracked and the Richardson number and internal wave climate followed during NATRE.

II. INSTRUMENTATION

A. Mechanical

The RiNo array consists of six acoustic current meters [6] spaced from 30 cm to 480 cm in the vertical. Thermistors were placed in each velocity measurement volume and SBE-3 temperature and SBE-4 conductivity sensors (Sea-Bird Electronics, Inc., Bellevue, WA) were placed at the ends, 510 cm apart. An SBE-16 SeaCat CTD (Sea-Bird Electronics, Inc.) in the center obtained the temperature-salinity relation for the water in which RiNo floated and measured the depth as a function of time. As RiNo drifted with the water, the relative flow over the sensor array was small, mostly due to the shear over the length of the measurement tower. A compass allowed the direction of the shear to be measured. Since RiNo was tethered to the Bobber, the shear over the depth difference of the two instruments gave a mean velocity to the flow over RiNo. RiNo was in effect towed by the Bobber.

1) *RiNo Frame:* The central tower of the acoustic current meter array is built of stainless steel cages, 10 cm in diameter. Thirty-five centimeter long sensor cages and 25 cm long spacer cages are bolted together for the sensor spacing required. The 230 cm long tower is guyed with stainless steel cable at the end and at its mid point. The base of the tower is supported on a plate at the top of the central buoyancy module. The guys attach to stainless steel welded corners of the central module. A similar tower is bolted and guyed to the bottom of the central module.

The central buoyancy module is a triangular prism 54 cm tall and 150 cm on a side. Except for the stainless steel corners, the central module is non-metallic. The nine edges are fiberglass angle stock. Vertical fiberglass plates extend from the midpoints of the sides toward the center, for mounting instrument cases and supporting the tower bases. Four 19" glass floatation balls in the central module provide buoyancy for RiNo. One ball is in the center, held in place by cuts in the fiberglass plates. Each of the other three balls is supported by its polyethylene hardhat bolted to a vertical edge and the top and bottom edges nearest to it.

Pressure housings for electronics, battery, and data logger are mounted on the fiberglass plates and an acoustic transponder, acoustic command release, SeaCat CTD, and Argos satellite beacon are also mounted there, Fig.1. At the lower end of the lower tower are two weight releases, one overpressure, the other a burnwire release. Additional buoyancy was required in the form of syntactic foam blocks which were secured with stainless steel hoseclamps to the pressure housings. All was trimmed to be neutrally buoyant at the target density surface near 300 meters depth. Air weight was 340 kg. The compressibility of the components gave an overall depth sensitivity to ballast of about 1 meter per gram.

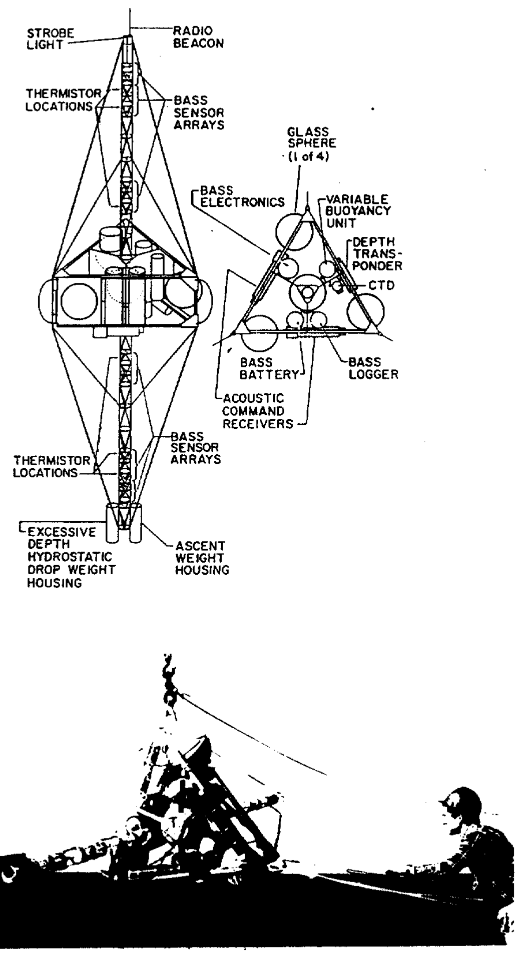

Fig.1. Line drawing of RiNo in elevation and plan view with acoustic current meters (BASS sensors), thermistors, CTD, and ascent weights. Photograph of RiNo launch in horizontal orientation.

2) *Cables:* Urethane jacketed coaxial cables connected the current meter transducers to the electronics. Approximately 300 meters of such cable is used in the RiNo float enclosing several hundred cubic centimeters of air. This provides initial compressibility much greater than water and requires that the float be over-ballasted in order to sink. However, once submerged, this volume decreases and makes the net compressibility less than that of water at 300 meters.

An effort was made to exclude traps where air might be caught at the surface. Despite this effort, several attempts were required to achieve neutrality submerged. During these ballast dives, sinking rates of 10 meters per day were observed, possibly due to air in the cables escaping or going into solution in the teflon and urethane insulation. The compression of the cables posed another concern for the proper behavior of RiNo, the calibration of the acoustic current meter with zero flow. Several calibration dives were required to determine the zero flow readings at pressure. These calibration dives were made with carrageenan and plastic bags [7].

3) *Interconnection to Bobber:* The Bobber is similar in size and weight to RiNo and normally carries a 4.8 kg recovery weight. Bobber contains a ballast pump and an isotherm following system enabling it to overcome the initial sinking of RiNo and the longer term creep of the pressure cases on RiNo. The recovery weight was transferred from Bobber to RiNo and a tether attached from RiNo to the weight dropper of Bobber. Bobber with RiNo tethered to it would be neutral at 300 meters, able to jettison RiNo instead of its 4.8 kg weight and return to the surface. RiNo would then sink with negative buoyancy of 4.8 kg.

The over-pressure weight release on RiNo, set for 1000 meters, would drop 9.6 kg, resulting in an instrument 4.8 kg buoyant, buoyant enough to extend its Argos antenna clear of the water. (The guy to which the Argos whip antenna is attached is non-conductive Kevlar rather than stainless steel.) Since upon release, Bobber rises and RiNo sinks, the tangle at the surface is avoided and each can be recovered independently.

During launch, first Bobber, then RiNo is put over the side. The tether was made long enough to accomplish the second operation with the Bobber in the water, 15 meters. Two meters of elastic shock cord, bypassed with 5 meters of extra cable, was connected in series to remove surface surge loads. The cable itself was plastic jacketed stainless steel wire with a swivel. At the upper end, the cable was shackled to a syntactic foam block shaped to fit in the release mechanism of the Bobber. This meant it was the same shape as the lead weight that was removed from the Bobber release. The lower end had the swivel and a shackle connecting it to the top of the upper tower of RiNo. Upon separation, the tether would stream up as the RiNo sank to avoid tangling the over-pressure release at RiNo's lower end.

4) Releases: An over-pressure release protected RiNo from going too deep and for recovery. The over-pressure release is a piston in a closed cylinder restrained from moving by a bolt, reduced sufficiently in diameter under its head to break at a predetermined pressure. The breaking of the bolt at 1000 m dropped the 9.6 kg weight secured by a strap under its head. A second release held the equivalent of the normal recovery weight of Bobber, 4.8 kg, on a burnwire controlled by an acoustic command receiver. Upon command, a positive voltage could be switched to the burnwire which would electrolytically plate away, dropping the weight. This release was solely for backup, not intended to be used but available if something else failed. The third release was an over-pressure release like the first that dropped a descent weight whose purpose was to pull RiNo beneath the surface and compress the trapped air to a volume small enough that the net compressibility of the instrument was less than that of water. It was set for 300 meters. To prevent too rapid a sinking with Bobber, this weight was 0.3 kg.

Command release of the 4.8 kg weight could return RiNo to the surface attached to Bobber. This was potentially dangerous since breakage of the tether at the surface was likely and could result in RiNo sinking again to 300 meters. Trapped gas, not yet dissolved, might provide surface buoyancy to keep it at the surface but the shock cord was added to the tether to extend the time for recovery before the tether broke.

B. Electronics

1) Data and Power: The acoustic current meter measures velocity with a differential travel time technique that has a noise level of 0.3 mm/s although the uncertainty in zero point can be ten times that [7]. Four acoustic axes determine the components of velocity at 45° to the horizontal plane and spaced 90° in azimuth. The four axes of each sensor are measured normally connected and reverse connected (to cancel electronic drift in circuits past the reversing switch) every second, the measurements taking a total of 8 ms. Reversed measurements are subtracted from normal measurements and stored as 16 bit integers for the 24 axes (6 sensors of 4 axes each).

Temperature is measured with six thermistors in precision resistor bridges multiplexed to an instrumentation amplifier. These are digitized every second too.

The current to take these one second samples is 15 ma. The samples are averaged every 30 seconds for recording. At the end of 30 seconds, the compass is read (a Grey code disk coupled to a gimballed magnetic card, read optically) and added to the averaged velocity and temperature data. These data with a time stamp are sent to a data logger in a separate case 23 hours per day. These averaged data can be recorded for a year in 100 MBytes, half of the storage in the logger. It also takes 3/4 of the battery charge, 126 ah.

Every 10 minutes, power is provided to a Digiquartz pressure sensor (Paroscientific, Inc., Redmond, WA) and the SeaBird temperature and conductivity sensors and their output frequencies are counted for 10 seconds. This increases the current from 15 ma to 72 ma and amounts to 1/16 of the battery charge, 10.5 ah. Every measurement of velocity, thermistor temperature, pressure, SeaBird temperature, SeaBird conductivity, compass, pitch, and roll is recorded for these 10 seconds. These data require 50 MBytes, one quarter of the storage in the logger. Ten seconds of counts from the SeaBird sensors is needed to resolve temperature to 0.001°C and salinity to 0.002‰.

At noon and midnight, power is provided to the Paros pressure sensor and SeaBird sensors for 15 minutes and the data are recorded continuously. This "event" mode consumes 8% of the battery charge, 13.1 ah. The data recorded in event mode takes 1/3 of the capacity of the logger. All together, these three types of record use 87.5% of the available 200 MBytes of the logger in one year. The logger itself requires about 5 ah to record 200 MBytes. The sum of these charge requirements amounts to 92% of the anticipated capacity of the batteries in RiNo, 168 ah at 22.5 v.

2) SeaCat CTD: A SeaCat Model 16 CTD with a pumped conductivity cell and 1400 meter Digiquartz pressure sensor was mounted on the RiNo float. The SeaCat had 256 kBytes memory for a measurement of temperature, conductivity, pressure and pressure temperature every 20 minutes. This would use 91% of the storage capacity in a year. For test dives, a shorter interval of 4 minutes was used.

C. Acoustics

1) Transponders and Depth Telemetry: Each RiNo had a transponder and acoustic command release (ACR) capable of transponding in reply to the ship's 12.0 kHz echo sounder. The acoustic command release listened at 12.0 kHz and replied at 12.5 kHz. The transponder listened at 12.5 kHz and replied at 11.5 Khz. Thus, if the ACR were enabled, it could answer the ship's echo sounder and also reflect a 12.5 kHz pulse from the sea surface that would excite the transponder to reply after a delay equal to the round trip travel time to the surface. The two replies on the echo sounder on the ship indicated the slant range and the depth of RiNo. There were 50,000 transpond pings available in the battery of each unit. At a ping every 8 seconds, 100 hours of depth tracking was possible. In practice, only a few hours per deployment was used.

2) Beacons and Relocation: Bobber transmitted a 250 Hz swept frequency signal (1.5 Hz in 80 seconds) every twelve hours for tracking and a telemetry signal to indicate the depth of the float. Based on these signals, we could determine if Bobber was maintaining depth. The 300 meter depth created a problem in tracking however in that the downward refraction in the near-surface water produced a shadow zone causing us to miss many transmissions with ship lowered hydrophones.

Bobber also had a high frequency beacon (10-12 kHz) that was useful for short range relocation. The source depth limited the range with the high frequency beacon to about 4 km. Again, this made shipboard tracking difficult.

Moored autonomous listening stations did receive the low frequency transmissions and permitted tracking the float during the entire period it transmitted. However drifting and ship lowered hydrophones were often unable to receive transmissions.

During the deployment cruise in May, 1992, floats were tracked by high frequency beacon. Frequent visits to the float position prevented them from becoming lost. On a sampling cruise in October, 1992, Bobber 61, the one to which RiNo was attached, was not heard or tracked. The recovery cruise in May, 1993 searched for Bobber 61 without success. It was thought during the recovery cruise that the shadow zone problem was responsible for the inability to hear Bobber 61 but subsequently recovered autonomous listening stations revealed the real problem: no transmissions.

The autonomous listening stations recorded signals from Bobber 61 until December 24, 1992, with telemetry indicating 300 meter depth. Then the signal stopped. The prospects for recovery of RiNo are poor, depending on tether failure or deep sinking of Bobber to release RiNo and activate the final recovery aid, Argos.

D. Radio

Argos satellite tracking permits drifting buoys to be found if the signal is received. RiNo contains an Argos transmitter, disabled by pressure switch, that will signal it is on the surface if it achieves 4 kg buoyancy, enough to lift its antenna clear of the water. Release of the 9.6 kg recovery weight will provide that buoyancy. The Argos beacon was a backup system to prevent losing RiNo at the surface if an operation after release caused the ship to become separated from RiNo. It was also provided as a warning system in case RiNo surfaced prematurely during its planned year long deployment. It may still provide a relocation mechanism.

III. SAMPLE DATA

A. Ballasting and Zero Calibration Dives

RiNo was assembled and trimmed for neutral buoyancy in

Woods Hole before shipment. The difference in density between Great Harbor and the target was used to calculate additional trim weight which was added. Then RiNo was disassembled and packed for shipment to Las Palmas, Gran Canaria. When reassembled, there was some concern that the trim was approximate, that components may have been deleted or added, and that there might have been a blunder in assembly requiring at least one ballasting dive before RiNo was attached to Bobber. To remain within Bobber's range of correction, RiNo was to be neutral within 50 gm at the target depth.

1) Ballasting: For a ballasting dive, all components that were to be used in a real deployment were mounted including the recovery weight, the tether and syntactic release block, batteries, and desiccant bags (sealed in plastic so they wouldn't absorb water before the final closure of the instrument cases). The 4.8 kg Bobber recovery weight was not mounted on RiNo. However the 9.6 kg recovery weight was mounted on a 1000 m over-pressure release and a 4.8 kg weight equivalent to the Bobber recovery weight was mounted on a burnwire release. An additional descent weight was hung on a 300 m over-pressure release but this weight was not part of the target assemblage.

Ballast dives with depth telemetry yield the descent rate before dropping the descent weight, a sinking or rising rate after dropping the descent weight, and possibly a rising rate after dropping the recovery weight. These rates give a drag coefficient, compressibility, and the buoyancy error at the target depth. RiNo was deployed several times to obtain a better correction of buoyancy errors. Repeated dives were necessary because zero calibrations are done concurrently with the ballasting dives and affect the buoyancy slightly.

2) Zeroing: After the cables are dressed on RiNo, it is necessary to measure the velocity, preferably at depth, with zero flow. Until NATRE, this was done by wrapping plastic bags around the sensors to reduce the flow, deploying RiNo for a ballasting dive, noting the velocity readings when the float was hovering, and using them to correct subsequent measurements. Before NATRE, a new technique was developed [7] that zeroed the flow even when RiNo was not hovering (but was at the proper depth). This involved casting carrageenan in the sensor volume to replace moving fluid with gel. The density of carrageenan matched that of seawater closely and was thought not to interfere seriously with ballasting. The zeros were excellent but the 25 kg of carrageenan gel cast on the sensors did affect the buoyancy and required a second and third reballasting without carrageenan gel to approach neutrality at 300 meters depth.

Damage to the tower on recovery to remove the gel required repairs and another zeroing deployment. Then the gel was replaced with plastic bags which provided high quality zeros since the float velocity was so low. These matched the zeros with the gel. However the buoyancy was in error enough that a second plastic bagged zero was needed to achieve neutral buoyancy at 300 meters. The zero acquired with bags on this ballasting dive was very clean.

B. Four Day Deployment

The ballasted and zeroed RiNo was launched with Bobber 60. The Bobber weight was added to RiNo. The plastic bags were removed (being very nearly neutral by test). The desiccant was opened. Bobber was launched first. Then the tether was attached to RiNo and RiNo was launched. The descent weight on RiNo carried the pair of instruments quickly to 300 m but they continued to sink until they were at 700 m depth. RiNo and Bobber 60 remained at 700 m for four days.

When Bobber 60 failed to correct the depth, a release was commanded. Bobber 60 failed to release the tether. Then the acoustic command release on RiNo was activated which returned Bobber 60 and RiNo to the surface tethered together. They were recovered and RiNo's four days of data were off-loaded. RiNo was redeployed on Bobber 61, which behaved correctly, sinking to 400 m and pumping itself back to 300 m. By contrast, Bobber 60 was relaunched and sank to 1000 meters and could not be recovered.

C. RiNo Data from 700 Meters

1) Format: Records of averaged data, stored every 30 seconds, are headed by "AA" for unpacking purposes. This is followed by the instrument identification number and the time the average was computed as month, day, hour, minute, and second. Next, the quality of the velocity averages is indicated by a single bit flag for any axis which had a missed measurement. Thus the 24 axes are represented by 3 quality bytes. The velocity averages come next as 24 two byte integers, the thermistor temperatures as 6 two byte integers, and pitch and roll as a pair of two byte integers. The next 12 bytes are reserved for pressure, Sea-Bird, and compass measurements but have no significance in the averaged data.

Event data, when they are transmitted, are headed by "EE" and the same identification, time, and quality information. The velocities are instantaneous values however. Thermistor temperatures, pitch and roll are also instantaneous. The next field is a three byte pressure measurement which is the cumulative count of the frequency output of the sensor. The next four words are 12 bit cumulative counts of the frequency output of the Sea-Bird sensors embedded in 16 bit words. The final byte has embedded in it a seven bit Grey coded compass. This compass, measuring orientation of RiNo every 10 minutes, was adequate to resolve its rotation.

2) Four Days of Shear: Fig.2 shows the four day record of velocity differences over the height of RiNo, 5 meters. Shears as high as 4.5 cm/s were observed although the average was 2 cm/s. Because the shear tended to force the float to align with it, there are few directional wraps and on the average, the shear is centered near 50°.

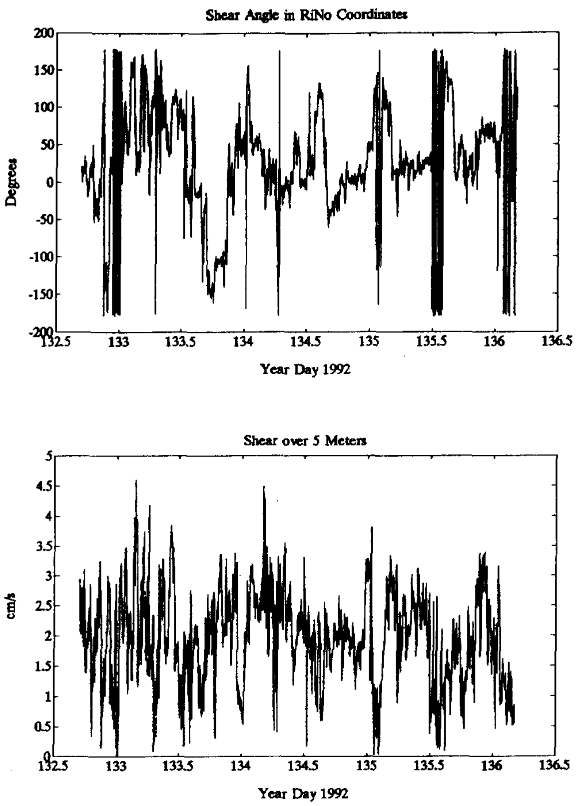

Fig.2. The difference in horizontal velocity between sensor 6 at the top of the RiNo tower and sensor 1 at the bottom, 5 meters below. The speed difference reaches 4.5 cm/s but the direction varies little owing to the tendency of RiNo to align with the flow.

3) Detail of Shear: The 30 second averages are rapid enough to resolve the fluctuations in the shear as can be seen in Fig.3. Even in the most rapidly fluctuating periods near year day 133.14, the measurements are not discontinuous. The shear remains above $7 \cdot 10^{-3}\ s^{-1}$ almost continuously for 40 minutes. The density gradients can be derived from the Sea-Bird measurements but have not been reduced yet. Thus a record of Richardson number at the 30 second scale and longer and for length scales from 5 meters to 60 cm is possible.

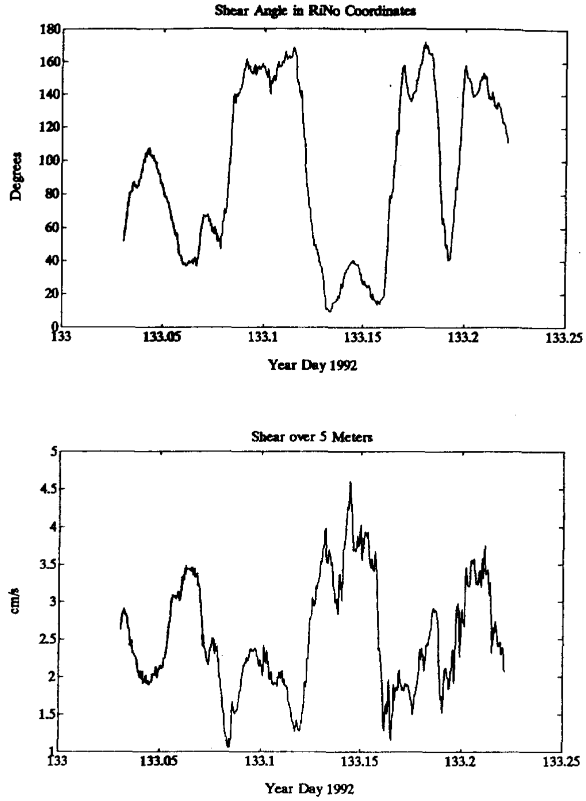

Fig.3. A 3 hour record of shear obtained from 30 second averages of 1 Hz measurements at two depths separated by 5 meters on RiNo. The shear exceeds $7 \cdot 10^{-3}\ s^{-1}$ almost continuously for 40 minutes.

REFERENCES

[1] J.S. Turner, *Buoyancy Effects in Fluids*, Cambridge University Press, 1973, pp. 91-102.

[2] Ibid., pp. 251-267.

[3] J.R. Ledwell, A.J. Watson, and C.S. Law, "Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment," *Nature*, in press.

[4] D.C. Webb, "SOFAR floats for POLYMODE," in *Oceans '77*, Vol. 2, IEEE, 345 East 47 St., New York, NY 10017, 1977, pp. 44B-1-44B-5.

[5] A.J. Williams, 3rd, C.H. Converse, and J.W. Nicholson, "Richardson number float," in *Current Practices and New Technology in Ocean Engineering*, OED Vol.12, G.K.Wolfe, Ed., ASME, 345 East 47 St., New York, NY 10017, 1987, pp.25-29.

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

[7] A.T. Morrison III, A.J. Williams, 3rd, and M. Martini, "Calibration of the BASS acoustic current meter with carrageenan agar," in *Oceans '93*, IEEE, 345 East 47 St., New York, NY 10017, in press.