From Swallow floats to Argo - the development of neutrally buoyant floats

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Abstract

Neutrally buoyant floats have been a vital tool in the exploration of the global ocean circulation and now provide a central element of the in-situ ocean observing system through the Argo project. The paper traces the development of neutrally buoyant floats from their origins in the mid 1950s to the present day and highlights areas of ocean science to which floats made significant contributions.

Introduction.

Since the 1950s, neutrally buoyant floats have been used in various forms to explore, and to discover, many aspects of the ocean circulation. This paper documents the development of these floats.

By late 2004 over 1500 neutrally buoyant floats were drifting at depth throughout the global ocean. They were approximately 50% of the final global Argo array that will be completed by 2007. Argo will form the core of the *in situ* ocean component of the Global Climate Observing System, essential for quantifying the oceans' response to climate change and to improving our understanding, and making improved predictions, of shorter-lived climate events.

The invention

In the summer of 1954, John Swallow, a 30 year old Cambridge PhD student, (Swallow, 1954) made his first visit to the National Institute of Oceanography (NIO)[1] in the countryside 30 miles SW of London. The visit was to discuss with NIO oceanographers the possibility of making direct measurements of the vertical profile of currents in the deep ocean. Cambridge scientists led by Tom Gaskell, and including John Swallow, had just completed the 1950-52 round-the–world voyage of HMS Challenger conducting seismic surveys (Ritchie, 1957, 1992). The idea was to employ sonobuoys, as used in seismic work, to track a slowly sinking acoustic source and hence to derive the current profile. Trials of the technique made by NIO scientists earlier in 1954 had not been successful due to the erratic movements of the moored sonobuoys (and also probably due to an inability to resolve the tidal/inertial oscillations). Following the visit, John Swallow accepted an invitation to join the staff of NIO and to further develop current measurement techniques and thus started this long technology development.

It is difficult to imagine just how little was known from direct measurements about the circulation of the deep ocean in the 1950s. Bowden (1954) could summarise all the current measurements reported in the scientific literature in a one page table and the longest of these measurements, made by instruments lowered from the ship *Armauer Hansen* in the 1930s (Ekman 1953), had only been able to give evidence of tidal signals.

Swallow quickly concluded that the sinking sound source method would not work. His work at Cambridge had made him familiar with the compressibility of materials and of seawater. He had experience of the measurement of acoustic travel times and knew about the difficulty of making deep-sea pressure seals. This experience led him to consider trying to stabilise a float at some level within the ocean so that it could be tracked acoustically and its drift integrated over an extended period. (Figure 1)

[1] The National Institute of Oceanography became the Institute of Oceanographic Sciences in 1976 and in 1990 became the IOS Deacon Laboratory (named after the NIO's founding director Sir George Deacon, FRS). In 1995 The IOSDL was incorporated in the Southampton Oceanography Centre.

Construction of the first floats started at the beginning of 1955. Materials and money were in short supply and so, as we say, "necessity was the mother of invention". Aluminium had the correct mechanical properties in terms of strength and density and the most readily available source of aluminium tubing was the scaffolding used in the construction industry. However, standard tubing had too great a wall thickness and so it had to be thinned by immersing the tubes in a bath of caustic soda. 6m of tubing were needed to provide sufficient buoyancy and for ease of handling this was cut into two 3m lengths laid side by side. A simple electronic circuit provided the 10kHz signal that drove a magnetostrictive nickel scroll sound source available from the Royal Navy. End caps were secured using the, then, new o-ring seals.

The floats weighed around 10kg in air but had to be weighed in water in order that they could be ballasted to stabilise at their target depth. This was done by suspending each float from a simple chemical balance mounted above a tube of salt solution (close to a salinity of 35 and mixed by repeatedly lowering a bucket down the tube and hauling it up again to prevent stratification) in the stairwell of the National Institute of Oceanography. The density of the saline solution was measured using high school physics techniques (specific gravity bottles). The floats needed only 38 g of negative buoyancy to stabilise at 1000m so great care was needed with the weighing and density calculations and to eliminate trapped air bubbles.

The first floats were deployed in June 1955 over the Iberian Abyssal Plain only 6 months after construction started. The original idea for tracking was that the floats would respond when they received a pulse from the ship's echosounder. This would have had the great advantage of measuring the floats' range directly. However the narrow echosounder beam made this impractical and an alternative method had to be developed. The first float was tracked for two and half days by determining its azimuth relative to the ship by using two hydrophones fore and aft and displaying their outputs on a cathode ray oscilloscope. (As the ship's heading changed so the signal arrivals would separate or converge and thus the heading on which the float was ahead/astern or abeam was determined).

It has to be remembered that at that time over much of the world's ocean, navigation was by sun and star sights and dead reckoning. The Iberian abyssal plain had an advantage in that there were small, isolated hills that could be used to give an absolute check the ship's position with the echo sounder. For the most part the ship's position was determined by taking radar fixes on a moored buoy (in 5000m of water with the uncertainty in position that this implies) and confirmed by positioning relative to the topography. Tracking the weak signals from the floats was made more difficult by the background of biological noise.

Of the 6 floats deployed, only two worked satisfactorily but nevertheless, the method had been demonstrated and the results reported by Swallow (1955) were detailed enough to show evidence of tidal variations. The float depth was calculated from the sequence of fixes to be around 600m.

While Swallow was engaged in this pioneering development, it seems that the neutrally buoyant float concept had also developed quite independently and simultaneously on the other side of the Atlantic. Henry Stommel (1955) had called for direct measurements of deep currents and had suggested that it might be done using subsurface neutrally buoyant floats. However his idea was that they should be tracked through the Sound Fixing and Ranging (SOFAR) channel by the floats creating regular explosions! Swallow had the advantage of a relevant practical background and worked in a lab where all the necessary components to build floats were accessible (even if they were second-hand). Stommel did not.

Over the next few years Swallow made further exploratory measurements in the Atlantic, gaining confidence in float ballasting, improving tracking techniques and using floats to depths as great as 2900m but with tracking still lasting no more that $2^1/_2$days. The measurements in April/May 1956 west of Gibraltar and in the Norwegian Sea in

October/November 1956 are reported by Swallow (1957). In this paper he comments on the variability of currents at depth, the comparison of these measurements with geostrophic shear calculations and the fact that a float close to the Mediterranean water core did not move westwards as it was expected to.

Swallow and Stommel had by then started to correspond. They met for the first time in 1955 when John Swallow went to New England (for a meeting to discuss radioactive waste disposal) and John was able to visit Woods Hole.

That visit too was significant in that it led to a collaborative study of the recently postulated (from geostrophic calculations and from theory, Stommel 1957, 1958) equatorward-flowing undercurrent beneath the Gulf Stream. The study was to use Woods Hole's *RV Atlantis* and the NIO's *RRS Discovery II*. In March/April 1957 9 floats were tracked for up to 5 days at depths of as great as 3000m. Compared with the earlier trials these might be regarded as much more "serious"; the float tubes were purchased rather than scavenged and the availability of LORAN navigation significantly reduced tracking uncertainties. The measurements confirmed the existence of southward currents of between 9 and 18 cm/s. (Swallow and Worthington, 1957)

The float tracking technique had proved itself to be robust (even if it did require John Swallow's personal attention) and capable of application to a range of depths and geographical locations. The Western Boundary Undercurrent work really marked the transition of float use from exploration to hypothesis testing – although much more exploratory work would follow.

By mid-1958 a further attempt (Swallow and Hamon, 1960) was made in the NE Atlantic to use floats systematically, to extend their lives and to compare the direct measurements with geostrophy. Rather than allowing the floats to signal continuously (their life in this mode was limited to 2 weeks), an internal mechanical clock programmed transmissions for 4hrs per day and thus extended float life to 12 weeks[2]. The site chosen was again on the Iberian Abyssal plain, close to that of the first measurements. The study measured currents from May 16 to July 13 with the longest-lived float abandoned, still working, after 48 days of (intermittent) tracking.

The results provided several examples of closely spaced floats having very different velocities and showed no "level-of-no-motion" but rather a sheared unidirectional flow between 1500 and 4300m. The ocean was not behaving as theory, or classical hydrography suggested it should.

The successful collaboration in the western boundary undercurrent and the exploratory work over the Iberian abyssal plain led to what is probably the best known early use of floats – the 1960 so-called *Aries* experiment led by John Swallow. (*Aries* was a 93 foot ketch that had been donated to WHOI in 1959). The *Aries* experiment aimed to provide evidence of the component of Stommel's hypothesis on ocean circulation that complemented the western boundary undercurrent; the existence of a slow basin-wide deep poleward recirculation.

Aries would be based in Bermuda and a series of long-life floats would be deployed about 200 miles west of the island and their positions fixed at approximately 2 day intervals. Navigation was greatly helped by the use of a LORAN C set constructed by Bob Walden of WHOI. The movement was expected to be slow enough to allow the floats to be found again even after port calls during the 14 month experiment. This strategy was based on the experience of the Iberian Abyssal Plain work.

The floats tracks immediately revealed some great surprises. At the chosen depths of 2000 and 4000m, speeds of the order of 10cm/s rather than the expected less than 1 cm/s

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[2] Mary Swallow (pers comm.) comments that these clocks were designed for use in Navy mines and had been purchased from military surplus shops in London's Tottenham Court Rd.. Their timekeeping at low temperatures was tested in the NIO cafeteria refrigerator. Doug Webb recollects being told by John Swallow of arriving by air in the USA for the *Aries* experiment with boxes that were ticking!

were found and both the floats and the observational strategy had to be altered to enable tracking to continue. It was also found that while floats separated by of the order of 10km behaved similarly, those with much greater separations behaved differently. The ocean mesoscale had been discovered and is encapsulated in the following quotation from Crease (1962). "…suggesting that half the energy is contained in eddies up to 40 nautical miles in extent". Although Swallow described the Aries experiment in a number of general articles it is surprising that it was not until much later (Swallow, 1971) that he himself described the *Aries* measurements in detail. However, the results of the measurements and the significance of the ocean mesoscale percolated through the international community by personal communication during the 1960s.

Capitalising on the discovery: basin scale measurements

Only a very small number of researchers used Swallow floats before the late 1960s. This was perhaps attributable to a degree of "mystique" about float tracking engendered by Swallow's attention to detail in float preparation and the difficulties of float tracking using low energy acoustic transmitters. (Nevertheless, an advertisement from Ocean Research Equipment Inc. (ORE) appears on the back cover of Deep Sea Research in February 1965 offering Swallow floats for sale).

This early limited use of floats contrasts with the larger number of laboratories that were measuring currents using moored instruments at that time (Gould, 2001). However moored current meters were also difficult to use for any period longer than weeks and especially close to the ocean surface. Most users were confined to the shelf seas.

In addition to the deployments already described, floats were used by NIO scientists in the Labrador Sea in 1962 , Figure 2, (Swallow and Worthington, 1969), in the Norwegian Sea outflow in 1963 (Crease, 1965), and in the Somali Basin during the International Indian Ocean Expedition (Swallow and Bruce, 1966). All these early float tracks were reworked and are documented in a set of 15 reports by Caston and Swallow published by the National Institute of Oceanography between 1969 and 1974. The last of these is Caston et al. (1974) and contains references to the earlier reports. At some juncture before 1966 the method of float tracking changed from hydrophones mounted on the ship's hull to two pairs of hydrophones, each pair towed on a cable deployed from the ships' quarter. The "square" of hydrophones separated by about 100m fore and aft and by the breadth of the ship could be towed at speeds of 3-4 knots (limited by ship and hydrodynamic noise) and could determine at what stage a float was abeam of the hydrophone array. This method significantly reduced float tracking time.

It can be argued that the discovery of an energetic ocean mesoscale exposed the limitations of ship-tracked floats. Continuous observations over months rather than days would be needed if the mean ocean circulation were to be revealed.

The development that addressed this problem was that by Tom Rossby and Doug Webb (Rossby and Webb, 1970) of floats that could be tracked by sound transmissions through the SOFAR channel. This harked back to Stommel's original SOFAR concept but used a low frequency (500-600Hz) sound source rather than his rather primitive idea of repeated explosions. The US Airforce maintained an array of Missile Impact Location (MIL) hydrophones that located the positions of test missiles that dropped SOFAR charges at the end of their flights. These hydrophones could monitor floats in much of the NW Atlantic.

The first two SOFAR floats (Figure 3) were deployed in the Sargasso Sea in 1968 and showed that reception of signals was possible at ranges of up to 1000km and that float positions could be determined with an accuracy of the order of 3-5km. The premature failure of both floats after 1 week and after 2 days (they were designed for a life of 9-12 months) was worrisome and attributed (without any real supporting evidence) to biological attacks on the floats. In 1969 a float operating at 380Hz was tracked for 4 months and confirmed the robustness of the technique. It produced a velocity estimate (2.8cm/s westwards) remarkably close to the summation of the earlier nearby *Aries* measurements. (Rossby and Webb, 1971).

The success of the SOFAR floats and the availability of the MIL hydrophones (and limited access to US Navy submarine-tracking hydrophones (note by an anonymous reviewer)) made it possible to carry out a systematic exploration of the ocean mesoscale over a substantial part of an ocean basin and thus paved the way for planning the 1973 Mid-Ocean Dynamics Experiment (MODE), (MODE Group, 1978). In MODE a combination of floats, moored current/temperature recorders, hydrographic surveys and bottom pressure gauges was used in a 9 month collaborative US/UK experiment.

20 MODE SOFAR floats, each with a 1 year design life, were deployed at a target depth of 1500m. The carrier frequency of their signals was lower (~270Hz) than in the earlier trials. The floats were tracked from four hydrophone sites, Bermuda, Bahamas, Grand Turk (a hydrophone purposely deployed for MODE) and Puerto Rico.

The data were captured on magnetic tape and on a graphic recorder. A local operator read and transmitted the arrivals from the graphic output and mailed tapes every few days.

Each float weighed around 430kg and was over 5m long. Ballasting was carried out in an enclosure attached to the Woods Hole dock. The floats also had a 10kHz, short range navigation system to allow their location and subsequent recovery by a ship. This system proved invaluable since on several floats the low frequency sound projectors quickly failed when the polyurethane disk separating the castor oil filling from sea water became unbonded. New disks were designed and fitted, the floats re-ballasted and redeployed.

The SOFAR floats, considering their relatively short development and trial phase, were remarkably successful. Only 6 of the 20 floats were lost and 2 were still being tracked two years after the start of the experiment. In fact, though the floats were supposed to be recovered at the end of the experiment they were left in the water since they were thought to be of more value out there than sitting in a store on land (Doug Webb. Pers Comm).

The restriction of SOFAR floats at that time to depths near the sound channel axis (due to depth restrictions on the pressure cases) meant that it was not possible to use these floats to explore the vertical structure of currents over most of the water column. (Swallow, 1977). For this purpose, John Swallow and his co-workers at NIO developed a ship-based system using transponding floats (returning to the tracking concept originally envisioned by Swallow) and made possible by improved transducers and micro electronics. The "MiniMODE" system (Swallow et al., 1974) allowed up to 18 floats to be tracked simultaneously (each identified by its own frequency in the range 5.0 to 6.5Khz). The floats responded to signals transmitted from an interrogator attached to a CTD/water sampler package so that hydrography and float tracking could be conducted simultaneously. This ability to interrogate from a wide range of depths allowed tracking of floats at all depths and the achievement of ranges of up to 70km (almost 2 minute signal travel time).

Ship navigation was based on TRANSIT satellite fixes interpolated by gyro compass and the ship's two-component electromagnetic log and by LORAN C. Float position errors were estimated to be of the order of 0.5km. Float depths could be estimated from either multiple fixes or by observing the delay of bottom reflections. However, the acoustic transducers were designed to project sound horizontally and so depth estimation from close overhead was problematical. The signal arrivals were recorded on a wet paper (and later on a dry paper) facsimile recorder and read by eye. The signals were also modified to produce an audio output. This filled the lab with a wonderful selection of random notes interspersed with noises from marine life and from the ship. It is a pity that none of these recordings survives.

Again, the floats could be recovered and 41 of 52 were retrieved. These floats were used at depths between 500 and 4000m and collected a total of 714 days of data over a 2 month period. This was approximately equal to the total number of ship-tracked float days accumulated during the previous 17 years!

The MODE marked a quantum leap in our ability to observe the state of the ocean. Although the experiment was still primarily ship based, the SOFAR floats enabled day-to-day objective mapping of the ocean mesoscale over an area 400km square and revealed the long term propagation of these features. (Freeland et al., 1975, Freeland and Gould, 1976). The floats were also entrained into Gulf stream rings and were thus able to reveal both their rotation rates and propagation. (Cheney et al., 1976)

Exploring on a basin scale

From the mid 1970s, acoustically tracked floats were used extensively to further explore the ocean's mesoscale structure and variability. However the use of floats was almost entirely applied to the North Atlantic. This bias was the result of the regional interests of the laboratories involved (Woods Hole, University of Rhode Island and the UK Institute of Oceanographic Sciences and of course the existence of the acoustic tracking network for SOFAR floats. The shorter range MiniMODE floats were applied to study a number of physical phenomena in detail.

The SOFAR float restriction to the western N Atlantic was removed by the development by Al Bradley and Jim Valdes of Autonomous Listening Stations (ALS) (Richardson et al., 1981). These were moored hydrophones with data recorders that recorded the signal arrival times from floats within acoustic range and were deployed on moorings with the hydrophones near the SOFAR channel axis. The use of subsurface moorings, to reduce mooring cost, risk of damage and acoustic noise, meant that data were not available in real time. ALS deployments of 6 months to a year were typical. (Figure 4)

As well as extending coverage in the western N Atlantic to include the Gulf Stream, the ALSs allowed SOFAR floats to be used in the eastern Atlantic. Here floats were deployed as a contribution to US efforts to study Meddies and to support US research in the US/Soviet POLYMODE experiment (Schmitz et al., 1988).

In the mid 1980s there was a considerable interest in the potential for the disposal of radioactive waste either below or on the sea bed. The feasibility studies included research on the interaction of radionuclides with sediment but also called for an investigation of ocean circulation around potential disposal sites. This required information on both the sub-thermocline mean circulation and on eddy-induced lateral mixing at these depths. Acoustically tracked floats were ideal for this purpose, and the presence of the Mediterranean water core at around 1000m resulted in a double sound channel with the deeper channel allowing tracking of floats at depths as great as 3000m at ranges of 1000km. (Gould, 1982).

However, floats operating at these depths could not use aluminium tube for pressure cases and instead floats were developed both in France and in the USA using glass spheres as pressure cases. A very deep Franco-German study was conducted within the framework of the North Atlantic Monitoring Programme (NOAMP) experiment, in which 14 floats at 3700m were tracked as part of a study of an OECD site for disposal of low-level radioactive waste near the Bay of Biscay. (Ollitrault et al 1988, Klein and Mittelstaedt, 1992).

In parallel, a UK experiment jointly between the MAFF Fisheries Laboratory, Lowestoft and the Institute of Oceanographic Sciences, tracked 13 floats over the Iberian Abyssal Plain and in the Canary Basin for periods up to 4 years at depths close to 3000m. These floats designed by Webb Research Corporation (WRC) used 4 glass spheres and transmitted at 260Hz. (Figure 5). (Rees and Gmitrowicz, 1989). The same float design was used in 1989 to study deep, cross-equatorial flows (Richardson and Schmitz, 1993).

WRC floats using two glass spheres were used in the western Pacific (Taira et. al. 1990). These transmitted at 625Hz and hence had smaller and lighter transducers than did the IOS, 260Hz "organ-pipe" resonators. ALSs also extended float coverage in the western basin of the Atlantic. SOFAR floats, as we have seen earlier, were large and cumbersome and their lifetime was limited by their need to carry large battery packs while still remaining neutrally buoyant. Despite this fact one float was tracked intermittently for 9 years (Owens et al, 1988).

The geographical restriction on long range float use was also removed by the development of floats that effectively inverted the SOFAR tracking system. This placed the bulky, heavy sound sources on moorings and thus enabled greater power output and longer life. These smaller, cheaper RAFOS floats developed by Tom Rossby and his group at the University of Rhode Island (Rossby et al., 1986; Rossby et al., 1993) record the signal arrivals from an array of moored sources and transmit the data back to satellites when they surface at the end of their mission. (The existence of Service Argos (established in the late 1970s) made the sustained operation of RAFOS floats a viable proposition). The floats were, and continue to be, used extensively both as traditional isobaric floats and by the addition of a compressible element, as isopycnal rather than isobaric floats. (Rossby et al., 1985). Such floats were small enough to allow successive releases from a moored near-bottom "float park" (Zenk et al 2000).

The scientific applications of floats of various types during the 1970s, 80s and 90s were numerous and significantly improved our understanding of the oceanic eddy fields and, to a lesser extent, the basin-scale mean circulation.

The topics explored include but are not restricted to:

- The origins, dynamics, history and distribution of discrete intense eddies
- The statistics of mesocale eddy variability on the scale of ocean basins
- The Gulf Stream and its dynamics
- Local oceanographic phenomena including flow interactions with topography and abyssal circulations.
- Pathways of cross-equatorial flow
- Internal wave dynamics
- The processes of winter convection, subduction and mixing

References to these and many other applications are included in a comprehensive list of publications on floats that can be accessed at (Insert URL). This list includes papers in the peer-reviewed literature, data and technical reports and newsletter articles. The references cover scientific research and technology developments. Acoustic float development and Lagrangian science issues are also documented in a book chapter by Tom Rossby (Rossby, 2005 In Press)

Use of floats as autonomous instrument platforms.

The earliest floats had little reserve buoyancy and were very primitive devices by today's standards. However, as float use increased it was recognised that in addition to being passive, quasi-Lagrangian current followers, floats could make other measurements. The earliest reference to this type of use is from Pochapsky (1961). Subsequently he studied both the horizontal and vertical internal wave motion with floats recording temperature and transmitting pressure data by means of a double ping with separation proportional to pressure/temperature (Pochapsky, 1963, 1966). Tracking was achieved via master and slave floats, a technique later adopted for the Minimode tracking system.

The second application of neutrally buoyant floats to the study of internal waves was a development by Doug Webb (Voorhis, 1968; Webb and Worthington, 1968). They added angled fins to a neutrally buoyant float so that it would rotate when water moved vertically past it (the float's orientation was sensed by a magnetic compass). Several of the SOFAR floats in MODE were instrumented to record pressure, temperature and vertical water motion. As well as being applied to studies of internal waves (Voorhis, 1968), this technique for measuring vertical velocities was particularly applicable to the study of deep winter convection and was used in the western Mediterranean in 1970 (Webb et al. 1970, Gascard, 1973) and much more recently in the Greenland and Labrador Seas, Lherminier and Gascard (1998).

A related use was the development of "Bobber" floats that could, by adjusting their buoyancy, profile between density/temperature surfaces making measurements of the changes in stratification. These were used in the NE Atlantic during the WOCE Subduction and North Atlantic Tracer Release Experiments (Price, 1996, Sundermeyer and Price, 1998). In a similar development an f/H RAFOS float was developed (Rossby et al., 1994) that measured the separation of density surfaces. The volume change needed to make the floats change volume was achieved by a piston attached to a screw thread and was driven by the motor from a cordless screwdriver.

D'Asaro et al , (1996) developed neutrally buoyant floats designed to track the three-dimensional motion of water in turbulent regions such as the upper mixed layer. The floats combined high drag, compressibility close to that of seawater and precise acoustic tracking. The floats could measure vertical displacement using pressure and combined with temperature, estimated vertical heat flux. A measurement of float rotation (c.f earlier work by Voorhis) permits measurement of vertical vorticity.

Adding a global dimension

The brief 100 day mission of SeaSat in 1978 (Cheney and Marsh, 1981), revealed for the first time how satellites carrying radar altimeters and scatterometers could provide quantitative global scale information relevant to the ocean circulation and the wind fields that force it.

Although it was not until much later that the successors to Seasat were launched, (Geosat 1985, ERS-1 1991, TOPEX-Poseidon 1992), these satellites and the development of floats, moored current meters, high quality CTD and tracer measurements opened up the possibility of a comprehensive study of the ocean on a global scale. The most important role played by the ocean is in the regulation of the earth's climate and this was to become the focus of the global approach. Planning for the World Ocean Circulation Experiment (WOCE) as part of the World Climate Research Programme, started in the early 1980s and resulted in an international effort to study the role of the ocean circulation in the earth's climate (see Chapters in Siedler et al., 2001).

While the planned new generation of earth observing satellites could provide the required global perspective, other, *in situ*, observing systems required an enhanced level of co-ordination, commitment and infrastructure if they were to be used on a global scale. Neutrally buoyant floats had operated only on the scale of ocean basins and the provision of a global acoustic float tracking network would have required far too great a level of commitment. A novel system was required to allow floats to be tracked globally. Thus, during the 1980s, Russ Davis and Doug Webb (Davis et al 1992) jointly developed the Autonomous Lagrangian Circulation Explorer (ALACE), a float that would have a multiyear life and could provide useful subsurface velocity information throughout the ice-free ocean. If acoustic tracking was impossible globally then the only alternative was to have the floats surface and be tracked by satellite. Both RAFOS and SOFAR floats had the capability of surfacing at the end of their mission by dropping a ballast weight either on a timer or by acoustic command. What was required for the ALACE was a capability to surface and return to depth repeatedly.

The solution to this problem lay in pumping fluid from within the pressure case into an external bladder to reduce the float's density and hence drive it to the surface. Deflating the bladder would return the float to depth.

The first prototype ALACE's were deployed in 1988 (Davis et al 1992) and the first were deployed as a contribution to WOCE in the Drake Passage in 1990 (Davis et al., 1996). The WOCE strategy was to make velocity estimates at a common level to provide velocity constraints on the global inverse calculations using hydrography, tracers and altimetry. Thus the level (near 1000m) was chosen on the basis of reducing sampling error rather than for the exploration of the structure of the global circulation. It was estimated that 5 years of data collected within each 500km square would reduce sampling error to 3mm/s over most of the ocean interior. This meant that 1000 floats each with a 5 year lifetime would be required. The rationale for various aspects of the WOCE float programme is described by Davis and Zenk, (2001).

The limitations of the single mission RAFOS floats (acoustic data downloaded only when the float surfaced at the end of its life) were relaxed by the development of a multi-cycle float, the MARVOR (named after the Breton name for a seahorse). MARVOR floats were acoustically-tracked but surfaced at regular (typically 3 month) intervals to transmit the signal arrival times. The process of ascent and descent was , as in the ALACEs, achieved by pumping fluid from an internal reservoir to an external bladder. (Loaëc et al 1994, Ollitrault et al 1994). MARVOR floats were first deployed in 1994 and were used in the South Atlantic SAMBA project and in the Eurofloat and Arcane projects in the NE Atlantic.

In total 1110 ALACE-type floats were deployed in WOCE. In large measure they achieved their objectives although not all achieved their target 5 year life many exceeded it and the longest-lived are still operating 8 years after deployment. The data have been used to construct velocity fields across entire ocean basins (e.g. Davis, 1998) and have been used to constrain inverse calculations. (e.g. Wijffels et al., 2001).

Present and future

The fact that at regular intervals (of the order of 10 days) each ALACE float would make a round trip to the sea surface led to their use as platforms for making other measurements. First profiles were made with only temperature sensors but, as small, low power, autonomous CTD sensors with good long-term stability were developed by Falmouth Scientific Instruments and SeaBird Electonics so full temperature and conductivity profiles were obtained, (Davis et al., 2001). These were profiling ALACEs (P-ALACE floats).

The ALACE and P-ALACE floats in WOCE were supplemented by just over 1000 floats of other types SOFAR, RAFOS and the French MARVORs (WOCE IPO, 2002). These were used for the exploration of basin scale circulation in many regions: in the NE Atlantic in the Eurofloat and other experiments (Bower et al 2002) , in the Brazil basin to explore its abyssal (Hogg and Owens 1999) and intermediate water circulations (Boebel et al. 1999) and in the Cape Basin and Agulhas current in the KAPEX studies (Boebel et al. 2002, Richardson et al. 2003). Autonomous floats were also used to study a number of physical processes: deep convection in the Labrador sea (Lavender et al., 2002, Steffen and D'Asaro, 2002), diapycnal mixing in the North Atlantic Tracer Release Experiment, (Sherman and Davis, 1995; Sundermeyer and Price, 1998) and subduction (Robbins et al, 2000).

The demonstrated ability of P-ALACE floats to collect high quality CTD data above and into the permanent thermocline (Bacon et al., 2001) and the success of the numerous deployments of ALACE and P-ALACE floats in WOCE pointed the way towards their use as a tool for prolonged global scale ocean monitoring that would complement and greatly enhance other elements such as altimetry, hydrography, XBTs etc. The resulting project is Argo. (See Chapter 3.2 in Koblinsky and Smith, 2001).

Argo's aim is to build up to and maintain an array of 3000 profiling floats measuring temperature and salinity between the surface and depths as great as 2000m throughout the ice-free regions of the ocean using floats derived from the P-ALACE and a profiling derivative of the MARVOR (PROVOR). Argo is a co-operative international effort based on the free accessibility and sharing of all data both in real time and after salinity data have been scrutinised and corrected.

The first Argo floats were deployed in 2000 and by mid-2004, over 1400 floats were delivering data. (Figure 6).

While the original neutrally buoyant floats were designed (primarily) to explore ocean circulation, Argo floats serve a dual purpose. Their primary contribution is the CTD profile data but velocity data from Argo have also demonstrated enormous potential despite the uncertainties due to their not being acoustically tracked and their departure from being truly Lagrangian due to time spent at the surface.

The references cited up to this point reflect the fact that neutrally buoyant float use in the 20th century was restricted to a relatively small number of laboratories and countries. Argo marks a radical broadening of the use of floats. Seventeen countries presently provide floats for the Argo array. The commitments range from the USA contributing half the floats to less than 5 floats contributed by countries such as Mauritius, Denmark, Ireland, Netherlands, New Zealand and the Russian Federation. Many other countries assist with float deployments and access to their Exclusive Economic Zones. Use of float data has broadened too. Operational centres use data from Argo in the production of ocean and climate analyses and forecasts. (Gould, 2004).

So, the concept originated by John Swallow and developed for global application in the 1980s and 90s, has grown from a rather exclusive research tool into a central element of the ocean observing system that addresses issues of global socio-economic significance (anthropogenic climate change, sea-level rise). Such a change was envisaged by Henry Stommel, 1989. In his, then, rather fanciful paper he describes the SLOCUM mission with autonomous instruments (more akin to the present day gliders) relaying information on the temperature and salinity of the upper ocean. One might argue that Argo in many ways fulfils Stommel's picture since it has already become the main source of CTD data from the open ocean. (Figure 7).

So what does the future hold? It seems that neutrally buoyant floats will remain a key element of ocean exploration and monitoring both in the global Argo programme and when used regionally to explore particular phenomena. Floats will carry a growing range of sensors. Oxygen probes (Emerson et al 2002) and CO_2 (Bishop et al., 2002) sensors are already in use (Trials are being made of acoustic sensors on floats to derive wind speed and rainfall and electromagnetic measurements measure the shear profile as a float rises). We have already demonstrated the potential for floats to act as monitors of ocean mixing through microstructure measurements and floats have now survived under Antarctic sea ice to download their profile data when spring arrives.

The list of applications seems endless and yet there are fundamental limitations. The stability of salinity sensors, while greatly improved, is still problematical for deployments of many years (Wong et al., 2003). Battery life remains a limiting factor if we need to profile deeper into the ocean. We lack a two-way data communication system with sufficient bandwidth and guarantees of long term (decades) availability that would enable the transmission of high resolution profiles, the diagnostic interrogation of floats and the potential to reprogram a float's mission.

We have arrived at our present exciting position thanks to a small number of far-sighted individuals and to a close and very productive interaction between ocean scientists and engineers. The solution to the problems outlined above depends on the continuation of that relationship.

With that in mind we can look forward to a very exciting era that was surely not envisaged by John Swallow when he scavenged the storerooms of the National Institute of Oceanography to build the first Swallow float.

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Figures

1) Facsimile of page from John Swallow's notebooks where the concept of neutral buoyancy was explored. The narratives of all of his research cruises are contained in a series of meticulous notebooks.

2) John Swallow (left) and Gordon Volkmann on R/V Erika Dan in 1962. The float shown here is essentially identical to floats deployed between 1957 and 1970 and using 10kHz magnetostrictive nickel scroll transducers. (Woods Hole Oceanographic Institution Archives)

3) Prototype SOFAR float. (Photograph courtesy of Tom Rossby)

4) Recovery of an Autonomous Listening Station. Cylinder contains batteries and electronics, Outboard of the pressure case is the linear hydrophone array. (Photograph, John Gould)

5) Deep SOFAR float using glass spheres. The uppermost sphere provides buoyancy, the middle two hold batteries and bottom sphere contains electronics. The float is seen in a deployment cradle that was opened hydraulically when the float was below the sea surface.(Photograph John Gould)

6) The global distribution of Argo floats in July 2004. (Argo Information Centre – http://www.argo.jcommops.org).

7) Yearly totals of the number of CTD profiles collected to depths of at least 1000m. When the 3000 float Argo array is complete it will deliver 100,000 profiles per year. Josh Willis, Scripps Institution of Oceanography.

References

Bacon, S., Centurioni, L.R., Gould, W.J., 2001. The evaluation of salinity measurements from palace floats. Journal of Atmospheric and Oceanic Technology 18(7), 1258-1266.

Bishop, J.K.B., Davis R.E., Sherman, J.T., 2002. Robotic observations of dust-storm enhancement of carbon biomass in the north Pacific. Science, 298, 817-821.

Boebel, O., Davis, R.E., Ollitrault, M., Peterson, R.G., Richardson, P.L., Schmid, C., Zenk, W., 1999. The intermediate depth circulation of the western South Atlantic, Geophysical Research Letters, 26 (21), 3329 - 3332.

Boebel, O., Rossby, H.T., Lutjeharms, J.R.E., Zenk, W., Barron, C., 2002. Path and variability of the Agulhas Return Current. Deep-Sea Research II, 50(1), 35-56.

Bowden, K.F., 1954. The direct measurement of subsurface currents in the ocean. Deep-Sea Research 2, 33-47.

Bower, A.S., Le Cann, B., Rossby, T., Zenk, W., Gould, W.J., Spear, K., Richardson, P.L., Prater, M.D., Zhang, H.-M., 2002. Directly measured mid-depth circulation in the northeastern North Atlantic Ocean. Nature, 419(6907),603-607.

Caston, G.F., Strudwick, W.K., Swallow, J.C., 1974. Neutrally buoyant floats serial nos 266-293 May 1973. Tables of times and positions. Diagrams showing trajectories and components of displacement. Institute of Oceanographic Sciences, Data Report No.2, 95pp.

Cheney, R.E., Gemmill, W. H., Shank, M. K., Richardson P. L., Webb, D.C., 1976. Tracking a Gulf Stream ring with SOFAR floats. Journal of Physical Oceanography, 6, 741-749.

Cheney , R.E., Marsh, J.G., 1981. SEASAT altimeter observations of dynamic topography in the Gulf Stream region. Journal of Geophysical Research, 86, C1, 473-483.

Crease, J., 1962. Velocity measurements in the Deep water of the Western North Atlantic. Journal of Geophysical Research, 67, 3173-3176.

Crease, J., 1965. The flow of Norwegian Sea Water through the Faroe Bank Channel. Deep-Sea Research, 12, 143-150.

D'Asaro, Eric A, Farmer, David M., Osse, James T., Dairiki, Geoffrey T., 1996. A Lagrangian float. Journal of Atmospheric and Oceanic Technology 13, 1230-1246.

Davis, R.E. 1998. Preliminary results from directly measuring mid-depth circulation in the tropical and South Pacific . Journal of Geophysical Research, 103, 24619-24639.

Davis, R.E., Webb, D.C., Regier, L.A., Dufour, J., 1992. The Autonomous Lagrangian Circulation Explorer (ALACE). Journal of Atmospheric and Oceanic Technology 9, 264-285.

Davis, R.E., Killworth, P. D., Blundell, J. R., 1996. Comparison of ALACE and FRAM results in the South Atlantic. Journal of Geophysical Research, 101(C1), 855-884.

Davis, R.E., Sherman, J.T., Dufour, J., 2001. Profiling ALACEs and other advances in Autonomous Subsurface Floats. Journal of Atmospheric and Oceanic Technology 18(6), 982-993.

Davis R.E., Zenk, W., 2001. Subsurface Lagrangian Observations during the 1990s. Chapter 3.2, pp 123-139 *In Ocean Circulation and Climate – Observing and Modelling the Global Ocean, Academic Press, International Geophysics Series,* Vol 77, 712pp. (Eds, G. Siedler, J. Church and J. Gould)

Ekman, V.W., 1953: Studies on ocean currents. Results of a cruise on board the Armauer Hansen in 1930 under the auspices of Bjørn Helland-Hansen. Geofys. Publik. XIX, (1)

Emerson, S., Stump, C., Johnson, B., Karl D. M., 2002. In-situ determination of oxygen and nitrogen dynamics in the upper ocean. Deep-Sea Research, Part I, 49, 941-952.

Freeland, H.J., Rhines, P.B., Rossby, T., 1975. Statistical observations of the trajectories of neutrally buoyant floats in the North Atlantic. Journal of Marine Research, 33, 383-404.

Freeland, H.J., Gould, W. J. 1976. Objective analysis of mesoscale ocean circulation features. Deep-Sea Research, 23, 915-924.

Gascard, J-C., 1973. Vertical motions in a region of deep water formation. Deep-Sea Research 20, 1011-1027.

Gould, J., and the Argo Science Team, 2004. Argo Profiling Floats Bring New Era of In Situ Ocean Observations. EoS, Transactions of the American Geophysical Union, 85,(19), 11 May 2004.

Gould, W. J., 1982. Long range acoustic propagation trials June-July 1982. RRS "Discovery" Cruise 130. Institute of Oceanographic Sciences, Internal Document No. 167. (Unpublished manuscript).

Gould, W.John, 2001. Direct measurement of subsurface ocean currents: A success story. pp193-211 in Understanding the Ocean (Eds Margaret Deacon, Tony Rice, Colin Summerhayes), UCL Press.

Hogg, N.G., Owens, W.B., 1999. Direct measurement of the deep circulation within the Brazil Basin. Deep-Sea Research II, 46(1/2), 335-353.

Klein, H., Mittelstaedt, E., 1992. Currents and dispersion in the abyssal Northeast Atlantic. Results from the NOAMP field program.□Deep-Sea Research,□39, 10A, 1727-1745.

Koblinsky,C.J., Smith, N.R., 2001. □Observing the oceans in the 21st century.□ Melbourne: GODAE Project Office, Bureau of Meteorology, 2001, xiii, 604 pp.

Lavender, K.L., Davis, R.E., Owens, W.B., 2002. Observations of open-ocean deep convection in the Labrador Sea from subsurface floats. Journal of Physical Oceanography 32(2), 511-526.

Loaëc, G., Ollitrault, M., Dumortier, C., Jegou, P., Le Reste, S., Cortes N., Moliera, J., 1994. MARVOR: a multicycle subsurface float. [6pp.] in, Oceanology International 94: the Global Ocean, Conference proceedings, Volume 1. Kingston-Upon-Thames: Spearhead Exhibitions. Various pagination.; 1994

Lherminier, P., Gascard, J.C.,1998. Drifting isobaric float response to deep convective activity in the Greenland Sea. Academie des Sciences. Comptes Rendus. Serie 2a. Sciences de la Terre et des Planetes,□326, no. 5, 341-346.

MODE Group, The, 1978. The Mid-Ocean Dynamics Experiment. Deep-Sea Research 25, 859-910.

Ollitrault, M., Tillier, P., Bodevin, I., Klein, H., 1988. Deep SOFAR float experiment in the Northeast Atlantic. Centre National pour l'Exploitation des Oceans, Brest, Rapports Scientifiques et Techniques, No. 11, 122 pp.

Ollitrault, M., Loaëc, G., Dumortier, C., 1994. MARVOR: a multicycle RAFOS float. Sea Technology 35, 39-44.

Owens, W.B., Richardson, P.L., Schmitz, W.J. Jr., Rossby, H.T., Webb, D.C., 1988, Nine-year trajectory of a SOFAR float in the southwestern North Atlantic. Deep-Sea Research 35, 1851-1857.

Pochapsky, T.E., 1961. Exploring subsurface waves with neutrally buoyant floats, Instrument Society of America Journal, 8, 34-37.

Pochapsky, T.E., 1963. Measurements of small scale oceanic motions with neutrally buoyant floats. Tellus, 4, 5352-362.

Pochapsky, T. E., 1966. Measurements of Deep Water Movements with instrumented neutrally buoyant floats. Journal of Geophysical Research, 71, 2491-2504.

Price, J.F., 1996. Bobber floats measure currents' vertical component in the Subduction Experiment. Oceanus, 39 (1) , p. 26.

Rees, J.M., Gmitrowicz, E.M., 1989. Dispersion measurements from SOFAR floats on the Iberian Abyssal Plain. pp.64-67 in, Interim oceanographic description of the north-east Atlantic site for the disposal of low-level radioactive waste, Volume 3, [ed.F.Nyffeler & W.Simmons] . Paris: Nuclear Energy Agency/OECD. 374pp.

Richardson, Philip L., Schmitz, William J. Jr., 1993. Deep cross-equatorial flow in the Atlantic measured with SOFAR floats. Journal of Geophysical Research*,* 98(C5), 8371-8387.

Richardson, P.L., Price, J.F., Owens, W.B., Schmitz, W.J.Jr., Rossby, H.T., Bradley, A.M., Valdes, J.R., Webb, D.C., 1981. North Atlantic subtropical gyre: SOFAR floats tracked by moored listening stations. Science, 213, 435-437.

Richardson, P.L., Lutjeharms, J.R.E., Boebel, O., 2003. Introduction to the "Inter-ocean exchange around southern Africa", Deep-Sea Research II, 50 (1), 1-12.

Ritchie, G.S., 1957. Challenger: The Life of a Survey Ship, London: Hollis and Carter, New York: Abelard Schuman, 1958.

Ritchie, G.S., 1992. No day too long: An hydrographer's tale, Edinburgh, Pentland Books.

Robbins, P.E., Price, J.F., Owens, W.B., Jenkins, W.J., 2000. The Importance Of Lateral Diffusion For The Ventilation Of The Lower Thermocline in the sub-tropical North Atlantic. Journal of Physical Oceanography 30(1), 67-89.

Rossby, T., Webb, D., 1970. Observing abyssal motion by tracking Swallow floats in the SOFAR channel. Deep-Sea Research 17, 359-365.

Rossby, T., Webb, D., 1971. The four month drift of a Swallow float, Deep-Sea Research 18, 1035-1039.

Rossby, T., Dorson, D., Fontaine, J., 1986. The RAFOS System. Journal of Atmospheric and Oceanic Technology, 3, 672-679.

Rossby, T., Ellis, J., Webb, D.C., 1993. An efficient sound source for wide-area RAFOS navigation. Journal of Atmospheric and Oceanic Technology 10, 397-402.

Rossby, T., Fontaine, Jim, Carter, E.C.Jr., 1994. The f/h float - measuring stretching vorticity directly. Deep-Sea Research, Part I: Oceanographic Research Papers, 41, 975-992.

Rossby, T., Levine, E.R., Connors, D.N., 1985. The isopycnal Swallow float – a simple device for tracking water particles in the ocean. Progress in Oceangraphy 14, 511-525.

Rossby, H.T., 2005. The evolution of Lagrangian methods in Oceanography, in Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics. Edited by A. Griffa, A. D. Kirwan, A. J. Mariano, T. Özgökmen, and T. Rossby. Academic Press.

Schmitz, William J Jr., Price, J. F., Richardson, P.L., 1988. Recent moored current meter and SOFAR float observations in the eastern Atlantic near 32N. Journal of Marine Research, 46, 301-319.

Sherman, J. T., Davis, R. E., 1995. Observations of temperature microstructure in NATRE. Journal of Physical Oceanography, 25, 1913-1929.

Siedler, G., Church, J., Gould, J., 2001. Ocean Circulation and Climate- Observing and Modelling the Global Ocean, International Geophysics Series, Volume 77. Academic Press, 715pp.

Steffen, E.L., D'asaro, E.A., 2002. Deep convection in the Labrador Sea as observed by Lagrangian floats. Journal of Physical Oceanography, 32(2), 475-492.

Stommel, H., 1955. Direct measurements of sub-surface currents. Deep-Sea Research, 2, 284-285

Stommel, H., 1957. A survey of ocean current theory. Deep-Sea Research. 4, 149-184.

Stommel, H., 1958. The abyssal circulation. Letter to the editors. Deep-Sea Research., 5**,** 80-82.

Stommel, H., 1989. The Slocum mission. Oceanography, 2(1), 22-25.

Sundermeyer, M.A., Price, J.F., 1998. Lateral mixing and the North Atlantic Tracer Release Experiment: observations and numerical simulations of Lagrangian particles and a passive tracer. Journal of Geophysical Research, 103(C10), 21481-21497.

Swallow, J.C., 1954. Seismic investigations at sea. University of Cambridge, PhD Thesis, 296pp. (Unpublished manuscript).

Swallow, J.C., 1955. A neutral-buoyancy float for measuring deep currents. Deep-Sea Research, 3, 74-81.

Swallow, J.C., 1957. Some further deep current measurements using neutrally buoyant floats. Deep-Sea Research, 4**,** 93-104.

Swallow, J.C., 1971. The Aries current measurements in the Western North Atlantic. Philosophical Transactions of the Royal Society London A, 270, 451-460.

Swallow, J.C. 1977. An attempt to test the geostrophic balance using Minimode current measurements. pp.165-176 in, A voyage of discovery, George Deacon 70th anniversary volume, (ed.M.Angel).Oxford: Pergamon Press. 696pp.

Swallow, J.C., Bruce, J.G., 1966. Current measurements off the Somali coast during the southwest monsoon of 1964. Deep-Sea Research, 13, 861-888.

Swallow, J.C., Hamon, B.V., 1960. Some measurements of deep currents in the Eastern North Atlantic. Deep-Sea Research, 6, 155-168.

Swallow, J.C., McCartney, B.S., Millard, N.W., 1974. The Minimode float tracking system. Deep-Sea Research 21, 573-595.

Swallow, J.C., Worthington, L.V., 1957. Measurements of deep currents in the western North Atlantic. Nature, 179**,** 1183-1184.

Swallow, J.C., Worthington, L.V., 1969. Deep currents in the Labrador Sea. Deep-Sea Research, 16, 77-84.

Taira, K., Kitagawa, S., Uehara, K., Ichikawa, H. Hachiya, H., Teramoto, T., 1990. Direct Measurements of mid-depth Circulation in the Shikiku Basin by tracking SOFAR floats. Journal of the Oceangraphical Society of Japan. 46, 296-306.

Voorhis, A.D., 1968. Measurements of vertical motion and the partition of energy in the New England slope water. Deep-Sea Research 15, 599-608.

Webb, D.C., Worthington, L.V., 1968. Measurements of vertical movement in the Cayman Basin . Deep-Sea Research, 15, 609-612.

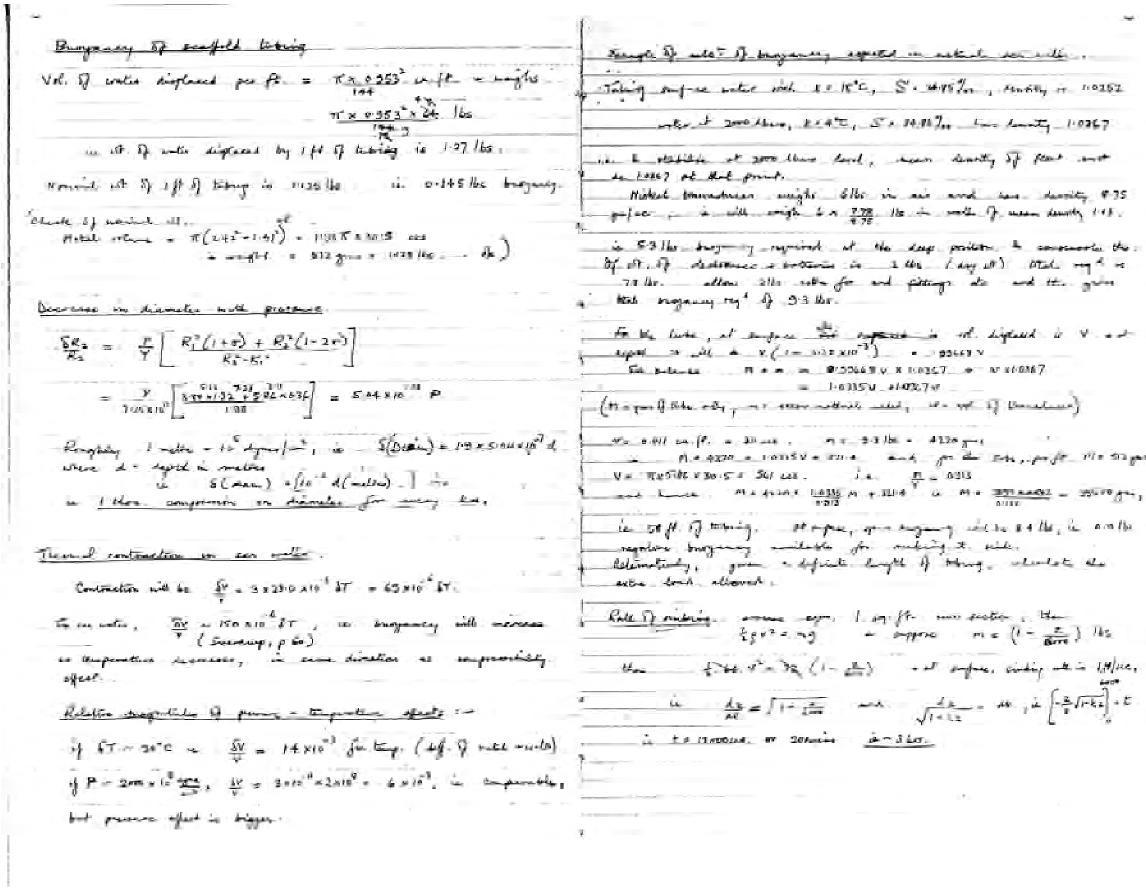
Webb, D.C., Dorson, D.L., Voorhis, A.D., 1970. A new instrument for the measurements of vertical currents in the ocean. Conference on Electronic Engineering in Ocean Technology. University College of Swansea, 21-24 September 1870. I.E.R.E. Provc., 19, 323-331.

Wijffels, S.E., Toole, J.M., Davis, R., 2001. Revisiting the South Pacific subtropical circulation: a synthesis of world ocean circulation experiment observations along 32°S. Journal of Geophysical Research, 106(C9), 19481-19513.

WOCE International Project Office, 2002. WOCE observations 1990-1998; a summary of the WOCE global data resource. WOCE International Project Office, WOCE Report No. 179/02. Southampton, UK.

Wong, A.P.S., Johnson, G.C., Owens, W.B., 2003. Delayed-mode calibration of Autonomous CTD profiling float salinity data by Theta-S climatology. Journal of Atmospheric and Oceanic Technology, 20(2), 308-318.

Zenk, W., Pinck, A., Becker, S., Tillier, P., 2000. The float park: A new tool for a cost-effective collection of Lagrangian time series with dual release RAFOS floats. Journal of Atmospheric and Oceanic Technology, 17, 1439-1443.



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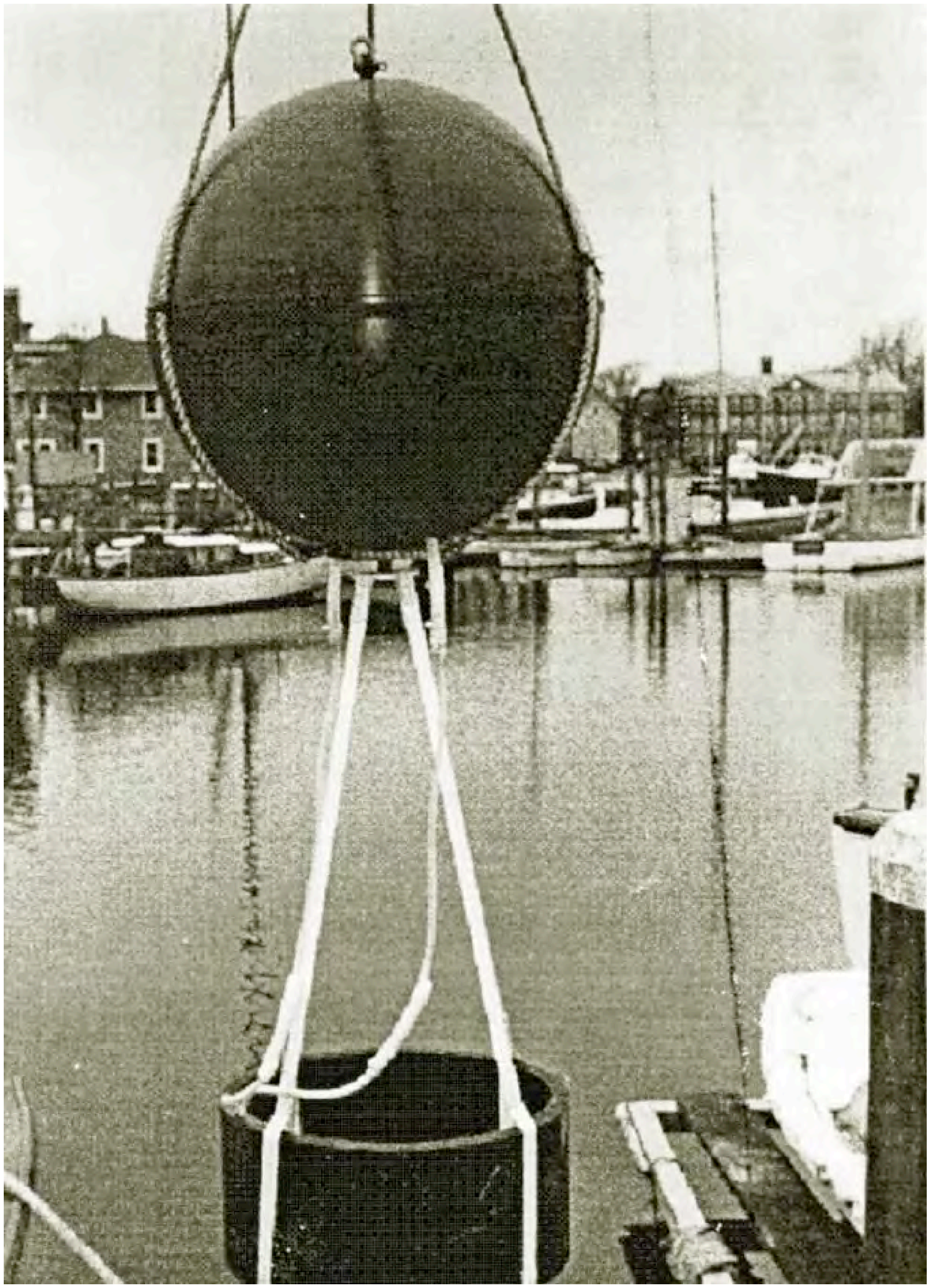

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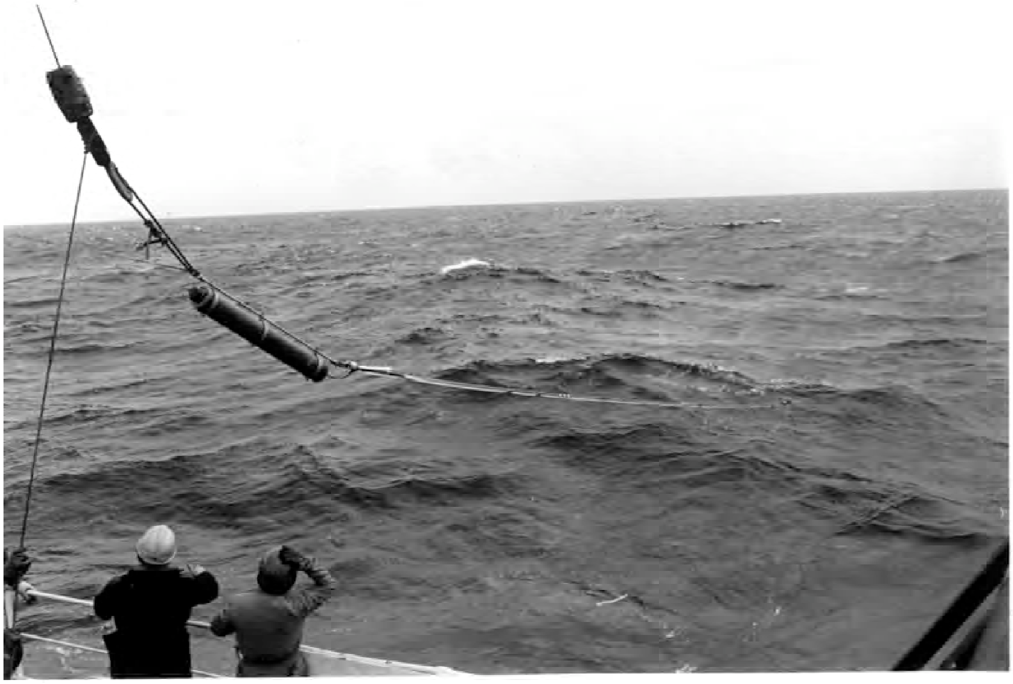

Figure 4 Recovery of an Autonomous Listening Station. Cylinder contains batteries and electronics, Outboard of the pressure case is the linear hydrophone array that is located below the electronics package. (Photograph, John Gould)

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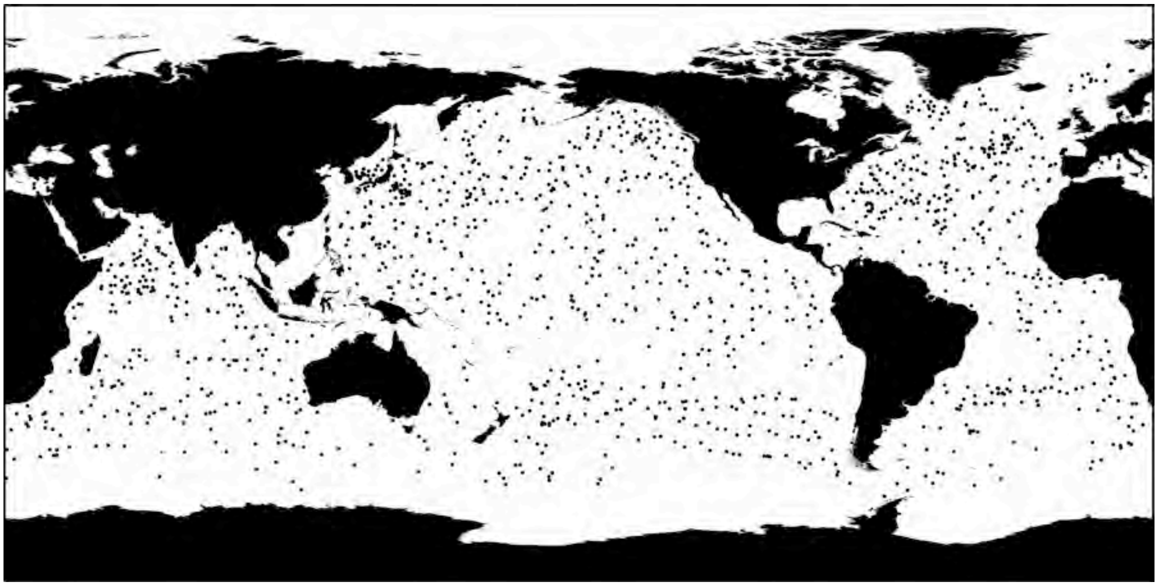

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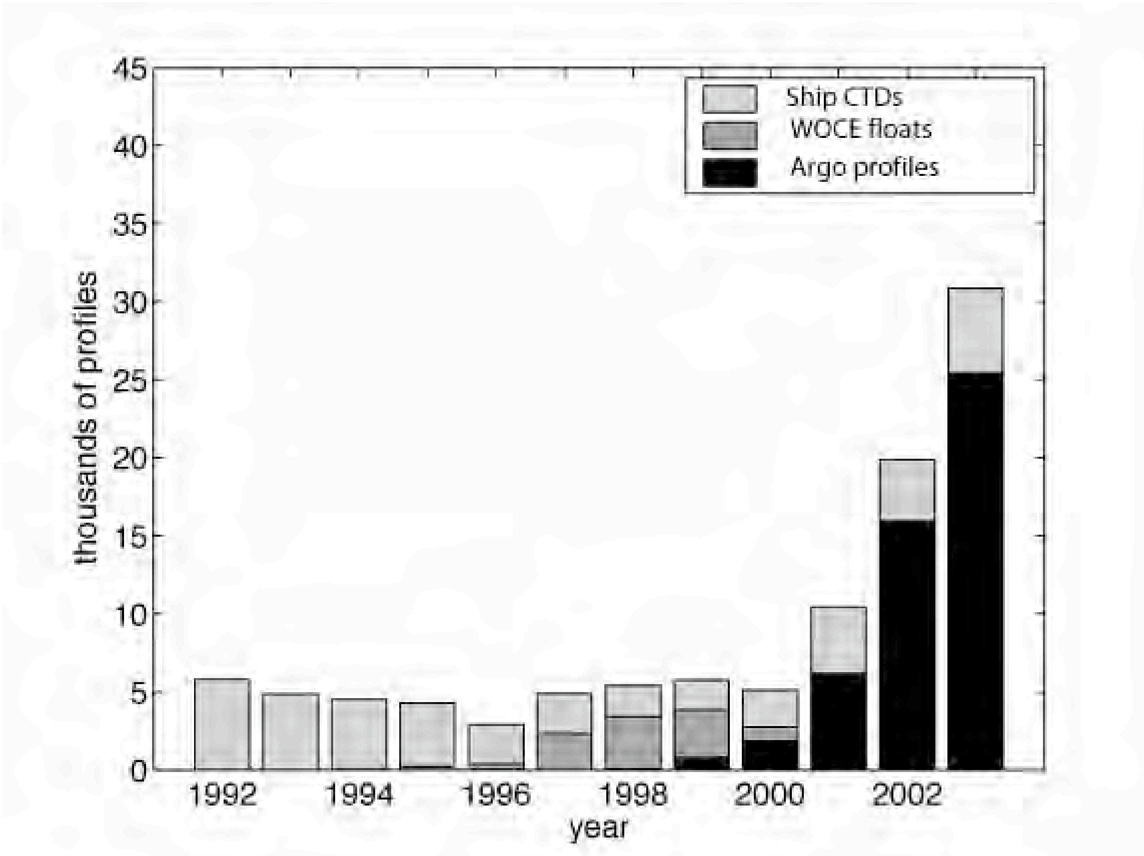

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