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The Isopycnal Swallow Float–A Simple Device for Tracking Water Parcels in the Ocean

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Abstract–A standard Swallow float can be converted into a passive, isopycnal follower by the addition of a 'compressee', a spring-backed piston in a cylinder designed to give the float the compressibility of seawater. Thus, no Archimedian buoyancy is created due to changes in depth. In addition, the float must have a coefficient of thermal expansion significantly smaller than that of seawater. An instrument meeting these requirements, ballasted to a chosen isopycnal, will approximately follow that isopycnal, on time scales longer than the local buoyancy period.

Two preliminary field experiments were conducted in the upper main thermocline near the North Wall of the Gulf Stream. During August 1981, a spherical glass float was deployed 200 km downstream from Cape Hatteras, and was tracked for approximately 100 km. Neutrally buoyant in the oxygen minimum near 380 m, the float tracked the $\sigma_T = 27.12 \pm 0.01$ as determined from CTD data during its passage through a mini-meander. During September 1982, a cylindrical float was tracked for approximately 100 km east of Cape Hatteras. Deployed in the Gulf Stream near the 250 m level, the float tracked the $\sigma_T = 26.74 \pm 0.01$ isopyncal surface during a gradual descent and cross-stream motion over the 24 hr sampling period. Thus, the floats tracked nearly isopycnally in both field tests.

Clusters of these instruments used in concert with hydrographic surveys have the potential for unique studies of mixing, entrainment and topographic effects.

1. INTRODUCTION

NEUTRALLY buoyant Swallow floats, and their larger counterparts, SOFAR floats, have been used as subsurface drifters in numerous studies of mesoscale circulation (i.e., SWALLOW, 1955; ROSSBY, VOORHIS and WEBB, 1975; PRICE and ROSSBY, 1982) and small-scale motion (i.e., VOORHIS, 1968; POCHAPSKY, 1963). These floats approximately track isobaric surfaces, and thus are not Lagrangian followers of water parcels in a strict sense. Their deviations from true isobaric tracking are due in part ot small but finite differences in compressibility and thermal expansion from that of seawater.

A better representation of Lagrangian motion, particularly in regions of strong baroclinicity and vertical motion, can be obtained from a Swallow float modified to follow isopycnal rather than isobaric surfaces. This can be accomplished by the addition of a 'compressee', which adjusts the effective compressibility of the float package to approximate that of seawater. If the coefficient of thermal expansion of such a float is much smaller than that of seawater, it will remain close to a given isopycnal surface because neither salinity nor temperature changes will affect the density of the float. Hence, it becomes an isopycnal float. We begin with a description of the principles of operation, design, and also discuss the dynamic response of the isopycnal float to vertical perturbations. This is followed by a discussion of the results of two pilot experiments conducted near the northern edge of the Gulf Stream.

2. PRINCIPLES OF OPERATION

A necessary condition for an isopycnal float is that its compressibility be matched to that of seawater. Thus, no 'Archemedian' restoring force is introduced due to pressure changes, as in the case of the standard Swallow float. For the standard (isobaric) float, the compressibility is typically 30–50% less than seawater; so if a float is depressed from its equilibrium depth, it compresses less than the surrounding seawater, gains buoyancy, and thus has a relatively larger restoring force than an equivalent parcel of water. This restoring force maintains the equilibrium depth of the float, which in turn may be affected by the difference in coefficient of thermal expansion of the float and seawater.

In order to modify the float compressibility to that of seawater, a compensation unit or 'compressee' is added to the system. In the following discussion we determine the proper volume change of the compressee, the effective coefficient of thermal expansion, and the restoring forces for the selected equilibrium surface for the isopycnal and isobaric modes of operation.

The system volume V_S can be expressed as the sum of the float volume V_F and the compressee volume V_C, where V_F includes all other components, as follows:

$$V_S = V_C + V_F. \tag{2.1}$$

Differentiating with respect to pressure yields

$$V_S\left(\frac{1}{V_S}\frac{\partial V_S}{\partial p}\right) = V_C\left(\frac{1}{V_C}\frac{\partial V_C}{\partial p}\right) + V_F\left(\frac{1}{V_F}\frac{\partial V_F}{\partial p}\right),$$

or

$$V_S C_S = V_C C_C + V_F C_F, \tag{2.2}$$

where C_S, etc. represent compressibilities. Similarly, differentiating (2.1) with respect to temperature yields:

$$V_S \alpha_S = V_C \alpha_C + V_F \alpha_F, \tag{2.3}$$

where α_S etc. represent coefficients of thermal expansion. We require that C_S equal the compressibility of seawater C_W. Substituting into (2.2) and solving for V_C:

$$V_C = \frac{C_W - C_F}{C_C - C_W} V_F = r V_F. \tag{2.4}$$

Thus, the closer the compressibility of the float is to that of seawater the smaller the volume change required of the compressee. Using (2.3) and (2.4) yields

$$\alpha_S = \frac{\alpha_F + r\alpha_C}{1 + r} \tag{2.5}$$

so α_S and α_F are comparable unless α_C is much larger than α_F.

We now derive expressions for the restoring force for 'isobaric' and 'isopycnal' floats. If a float is displaced a small distance in the vertical, Δz, it experiences a change in volume, ΔV, due to pressure and temperature

$$\Delta V = \frac{\partial V}{\partial p}\Delta p + \frac{\partial V}{\partial T}\Delta T,$$

which can be written

$$\Delta V = V\left(\frac{1}{V}\frac{\partial V}{\partial p}\right)_T \frac{\partial p}{\partial z}\Delta z + V\left(\frac{1}{V}\frac{\partial V}{\partial T}\right)_p \frac{\partial T}{\partial z}\Delta z, \tag{2.6}$$

where $\partial p/\partial z$ and $\partial T/\partial z$ are the hydrostatic pressure and *in situ* temperature gradients, respectively, and $(1/V\ \partial V/\partial p)_T$ and $(1/V\ \partial V/\partial T)_P$ the volume expansion coefficients, are evaluated for constant temperature and pressure, respectively. It is assumed that the float is in thermal equilibrium with its surroundings, i.e., its temperature equals that of the medium.

For a small vertical displacement, Δz, the volume change for the iosbaric and isopycnal floats per unit displacement and volume are:

$$\text{[isobaric, }(B)\text{]} \qquad \frac{\Delta V_B}{V_F \Delta z} = C_F \frac{\partial p}{\partial z} + \alpha_F \frac{\partial T}{\partial z}\,; \tag{2.7}$$

$$\text{[isopycnal, }(S)\text{]} \qquad \frac{\Delta V_S}{V_S \Delta z} = C_S \frac{\partial p}{\partial z} + \alpha_S \frac{\partial T}{\partial z}\,. \tag{2.8}$$

The corresponding change in volume of isohaline seawater per unit displacement in the vertical would be:

$$\frac{\Delta V_W}{V_W \Delta z} = C_W \frac{\partial p}{\partial z} + \alpha_W \frac{\partial T}{\partial z}\,. \tag{2.9}$$

The restoring forces per unit volume and displacement for the two cases are thus:

$$F_B = \rho g \left[(C_W - C_F) \frac{\partial p}{\partial z} + (\alpha_W - \alpha_F) \frac{\partial T}{\partial z} \right], \tag{2.10}$$

for the isobaric case
and

$$F_S = \rho g \left[(\alpha_W - \alpha_S) \frac{\partial T}{\partial z} \right], \tag{2.11}$$

for the isopycnal case since $C_S = C_W$. For a water parcel where $\partial S/\partial z \neq 0$, an additional restoring force $\beta_W\ \partial S/\partial z$ is added to (2.10) and (2.11), where $\beta_W = 1/V\ \partial V/\partial S$.

In order to estimate the restoring force in (2.10) and (2.11) we first compute equivalent coefficients of thermal expansion which take into account observed salinity gradients. In Table 1 physical constants are presented for various float configurations and materials and for seawater. In the western North Atlantic the salinity gradient is positive upward, which means that the density decreases less rapidly in this direction than for the isohaline case. For this discussion, we include the salinity effect by reducing α_W from $1.7 \times 10^{-4}\,{}^\circ\mathrm{C}^{-1}$ to $0.6 \times 10^{-4}\,{}^\circ\mathrm{C}^{-1}$, corresponding to the western North Atlantic (worst case) condition. Using the equivalent coefficients of thermal expansion the restoring forces per meter displacement for aluminum floats and glass pipes (assuming a volume of $10^4\,\mathrm{cm}^3$) are:

$$\begin{aligned} F_B(\mathrm{Al}) &= 25 \text{ dynes;} \\ F_S(\mathrm{Al}) &= 6 \text{ dynes;} \\ F_B(\mathrm{gl}) &= 37 \text{ dynes;} \\ F_S(\mathrm{gl}) &= 17 \text{ dynes.} \end{aligned}$$

Thus, it is possible to construct isopycnal Swallow floats of glass, but the above numbers suggest that the restoring forces may be quite marginal for aluminum floats in regions of strong positive salt gradients. In weaker or negative salinity gradients aluminum (or other metals) will work fine, but they will not be isopycnal floats if there are large variations in T/S properties on constant density surfaces, as observed along the upper layers of the Gulf Stream.

TABLE 1. PHYSICAL CONSTANTS FOR VARIOUS MATERIALS

Material	Wall Thickness (in) (cm)	Diameter (in) (cm)	Compressibility (decibar^{-1} × 10^6)	Coefficient of Thermal Expansion (°C^{-1} × 10^4)
Aluminum Tubing	5/8 (1.60)	12(30.5)	− 2.5	0.71
Glass sphere	3/8 (0.95)	10(25.4)	− 2.6	0.096
Glass tube	13/64(0.52)	3 (7.6)	− 2.8	0.096
Seawater	–	–	− 4.4	2.26(@ 15°C, 36.0‰) 0.99(salt adjusted)
Total Float	–	–	− 3.6	0.18

3. FLOAT RESPONSE

Following the approach of VOORHIS (1971) the vertical equation of motion for an isopycnal float can be approximated by the equation for a forced damped harmonic oscillator

$$m^* \frac{d^2 Z_r}{dt^2} + \left(\frac{C\nu}{a^2} + DZ_r'\right)\frac{dZ_r}{dt} + kZ_r = k'Z_w, \tag{3.1}$$

where Z_r represents relative displacement between the float and the surrounding fluid, and Z_w represents the fluid motion relative to a fixed earth reference frame. Here, m^* is the sum of instrument and virtual mass, C and D are the linear and form drag coefficients, ν is kinematic viscosity, and a is the float radius. The quantities k, k' refer to restoring force coefficients due to the relative and absolute water motion, respectively.

The virtual mass contribution to the first term of (3.1) includes the effects of viscous drag and stratification. The second term of (3.1) includes the effects of linear drag, form drag, and stratification (i.e. internal wave production by the oscillating float). The restoring force constants, k and k' are dependent on material properties of the float and surrounding fluid, i.e., their compressibilities and thermal expansion coefficients, and the degree of vertical stratification in the local temperature and density fields. For our application, the two compressibilities are virtually identical.

Application of VOORHIS' (1971) results for an isopycnal-following float suggest that the float will closely follow density surfaces over time scales longer than the local buoyancy period.

4. DESIGN

The float used in our first test, August 1981, was packaged in a standard 25 cm glass sphere. Two seawater connections drilled through the sphere connected the external 12 kHz transducer with its power source. Temperature was measured by a thermistor in thermal contact with the sphere wall. It was encoded into a 12 digit binary word which was transmitted by the transducer every five minutes. The signal was displayed in analog form on the ship's graphic recorder. This binary printout was then read and converted to decimal form. The aluminum 'compressee' consisted of a spring-backed piston set in a cylinder made from solid aluminum stock, with an O-ring set in the piston wall.

The updated float design [Fig. 1(a)] used in September 1982 was packaged in a 1.52 m glass tube with a 7.6 cm nominal ID manufactured by the Corning Glass Co. One end of the tube was rounded at the factory, while the lower end closure assembly consisted of an aluminum

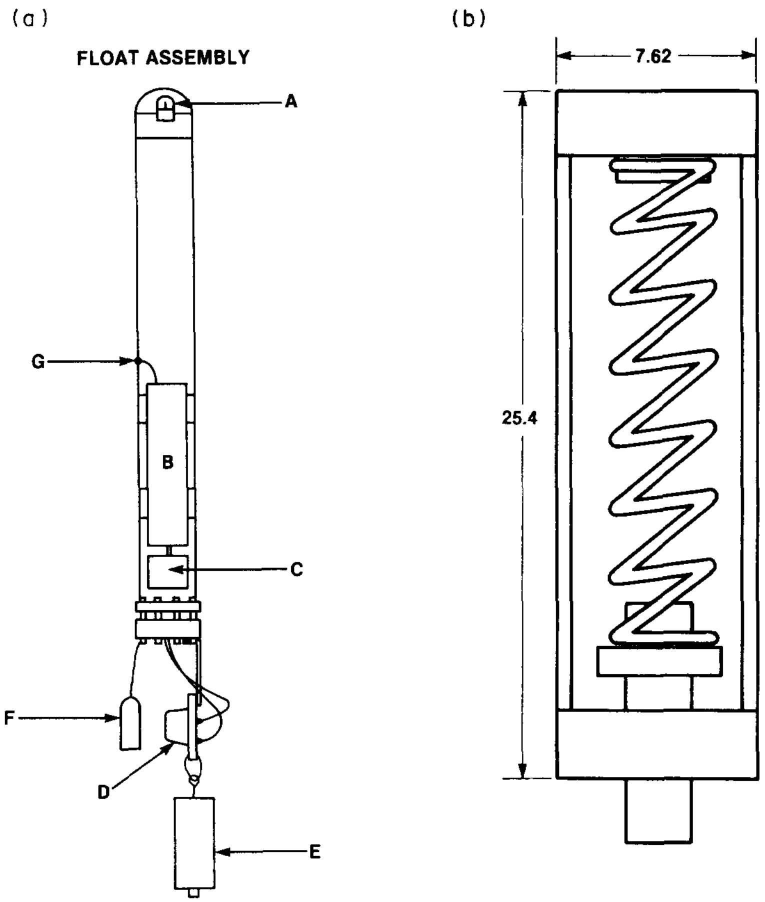

FIG. 1(a). Schematic diagram of the cylindrical isopycnal follower: (A) Flasher; (B) Electronics; (C) Batteries; (D) Transducer; (E) Compressee; (F) Expendable Ballast; (G) Thermistor. FIG. 1(b). Schematic diagram of compressee. The diameter of the piston and the spring constant are adjusted so that the compressibility of the float assembly matches that of seawater.

end plate, a teflon gasket, and two polypropylene fastening rings with stainless steel screws. For a detailed discussion of the glass tube and end plate design characteristics see ROSSBY and DORSON (1983). The advantages of this design are the lower cost of glass tubing over glass spheres, and the simplicity of installing sea connectors in a flat metal end plate. The electronics package incorporated a micro-processer programmed to: sample temperature at two minute intervals, average/encode, in binary form, four consecutive samples and store four hours of continouously updated data to be transmitted acoustically via the 12 kHz transducer every 15 minutes. Provisions were also made for an optical start/stop of the sampling sequence, unique coding (identifiers) for up to eight floats and capability to input, store, record and transmit data from a second sensor. In this design an expendable lead ballast is suspended from a loop of inconel wire which is electrolytically dissolved, after a preprogrammed number of data cycles. The ballast is sufficient to provide approximately 30 cm of freeboard at the sea surface. A flasher is actuated externally prior to launch and a semi-rigid PVC plastic bridle is used to facilitate recovery.

The compressee [Fig. 1(b)] used in the 1982 experiment contained a spring-backed piston, with diameter 2.25 cm, set in an aluminum cylinder made of tubing and machined end plates. The cylinder had an outer diameter of 7.57 cm, and an overall length of 25.35 cm. The piston was made to protrude approximately 2.54 cm from the end plate to provide better alignment at high pressures, and had an O-ring set in the piston wall. All parts were anodized to minimize salt water corrosion.

5. METHODS

5.1. *Ballasting*

The equation for determining the additional ballast, Δm, to bring the float from neutral buoyancy in the ballasting tank to the desired neutral buoyancy in the ocean is simply

$$\Delta m = (V_{P,T,S})_I \cdot (\rho_{P,T,S})_I - (V_{P,T,S})_B \cdot (\rho_{P,T,S})_B \tag{5.1}$$

where the subscripts refer to the *in situ* and the ballast tank values, respectively. The float is brought to neutral buoyancy in the laboratory in water of known density (known pressure and temperature) and its volume is determined by Bernoulli's displacement method. By giving the float constant coefficients of thermal expansion and compressibility we obtain

$$V_I = V_B\left(1 + \frac{1}{V}\frac{\partial V_B}{\partial T}\Delta T + \frac{1}{V}\frac{\partial V_B}{\partial p}\Delta p\right),$$

and (5.1) becomes

$$\Delta m = V_B[(\rho_I - \rho_B) + \alpha\rho_I\Delta T + \gamma\rho_I\Delta p], \tag{5.2}$$

in which all quantities are known or can be determined by measurement.

In practice we have found isopycnal ballasting to be very tricky if it is attempted at atmospheric pressure due to the presence of bubbles. Pressurizing the instrument (even to tap water pressures) will reduce the occurrence of bubbles and insure that all mating surfaces and O-rings are thoroughly pressed into place so that the volume of the float is well-defined and stable. If neutral buoyancy can be measured at the desired operative pressure equation (5.2) reduces to

$$\Delta m = V_B[(\rho_I - \rho_B) + \alpha\rho_I\Delta T] \tag{5.3}$$

Neutral buoyancy in the ballasting tank is easy to establish by measuring the length of a light chain lifted by the float.

5.2. *Testing*

Laboratory calibration of all complete compressees and individual springs were conducted on an Instron stress–strain instrument prior to use. In the two pilot experiments described in this paper, the compressee designs were basically the same with the piston diameters and spring constants adjusted to produce a combination which gave a proper compressibility to the float. The spring constants, alone and in the compressee, were found to match nominal manufacturer specifications, 730 lb/inch, upto 1200 psi, the maximum pressure of interest for our experiment. Creep of the compressees at a typical pressure of 600 psi was too small to be measured over a two day observation period. Hysteresis due to striction of the piston on the order of 10–20 psi was reduced to approximately 2% by choosing O-rings of high durometer.

All glass cylinder-end plate assemblies were pressure tested to several thousand psi. Teflon gaskets were preformed to the cylinder lip and marked for proper orientation for later use. Subsequent to the experiments described in this paper, we have improved the closure design by grinding flat the open end of the glass tube and using a very thin teflon gasket. This greatly reduces the volume change associated with cold flow of the teflon.

Temperature, i.e., thermistor resistance, was transformed into frequency in a simple RC circuit. Temperature calibrations are made for the electronics-thermistor combination with a fifth order polynomial equation determined to fit frequency data to actual centigrade temperature values.

5.3. *Float assembly*

The electronics, flasher and power packs are seated in foam rubber, in order to avoid points of concentrated stress on the inside walls of the glass tube. The batteries are placed at the lower end of the float to facilitate replacement and provide vertical stability, especially at the sea surface. Bolts with washers connecting a polypropylene collar provide sufficient closure to prevent low pressure leakage. The retrieval bridle is attached to the collar rather than the glass to prevent non-uniform stresses in the glass pipe.

5.4. *Launching/tracking*

The 10 kg instrument is lowered to near the water line, the ship is headed up into the current and floats are released manually. Instrument position is determined from LORAN fixes made while the ship is directly overhead of the float, shown schematically in Fig. 2. In the region of the study off Cape Hatteras the LORAN positions obtained with a Northstar 6000 have a typical resolution of about 0.1 micro seconds, using the 9960 chain and stations located at Nantucket Island, MA. and Carolina Beach, N.C., and are estimated to a precision of about 50 m (A. T. Massey, *pers. Commun.*). For float depths of approximately 400 m it is estimated that the float position error introduced by non-overhead fixes is less than 100 m. Poor quality overhead fixes are rejected when identified. The depth of the float is determined from the arrival times of the bottom reflected and surface-bottom reflected transducer signals and has an estimated resolution of 5 metres in the present system.

Subsequent to the ballast weight release, the float can be located at the sea surface by the flasher during nighttime, the brightly colored upper portion during daylight, and by the acoustic signal which continues to transmit at the surface. Recovery is accomplished by snagging the PVC bridle with boat hooks and lifting it directly on board. To date we have had five succesful recoveries of the cylindrical floats (including two passages under the ship's keel).

6. PILOT EXPERIMENTS

6.1. *August 1981*

The first deployment and tracking of the spherical isopycnal-following float occurred during a 30 hour period during August 25–26, 1981. This initial experiment demonstrates float behavior in a region generally characterized by only moderate depth changes in isopycnals, although the passage through a mini-meander does demonstrate its isopycnal character. It was launched at 36°39.02′N 73°13.36′W, (Fig. 3) near the northern edge of the Gulf Stream as

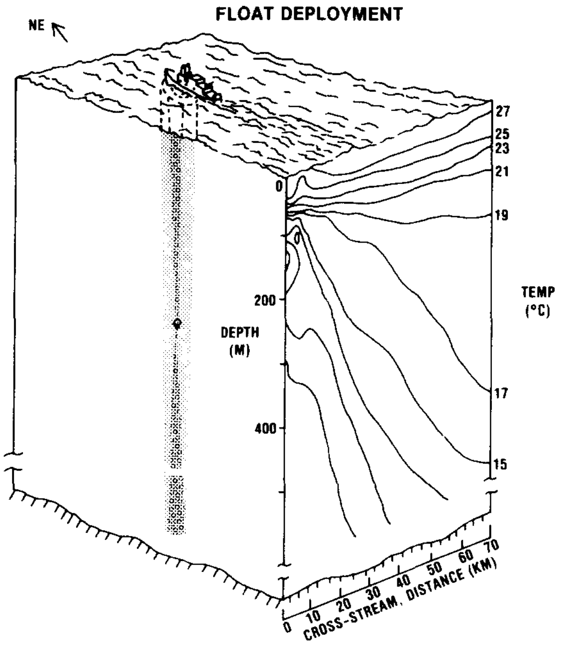

FIG. 2. Schematic diagram of the tracking scenario showing the float, and the direct and bottom reflected acoustic paths. The upstream temperature section from the August 1981 pilot experiment is also shown.

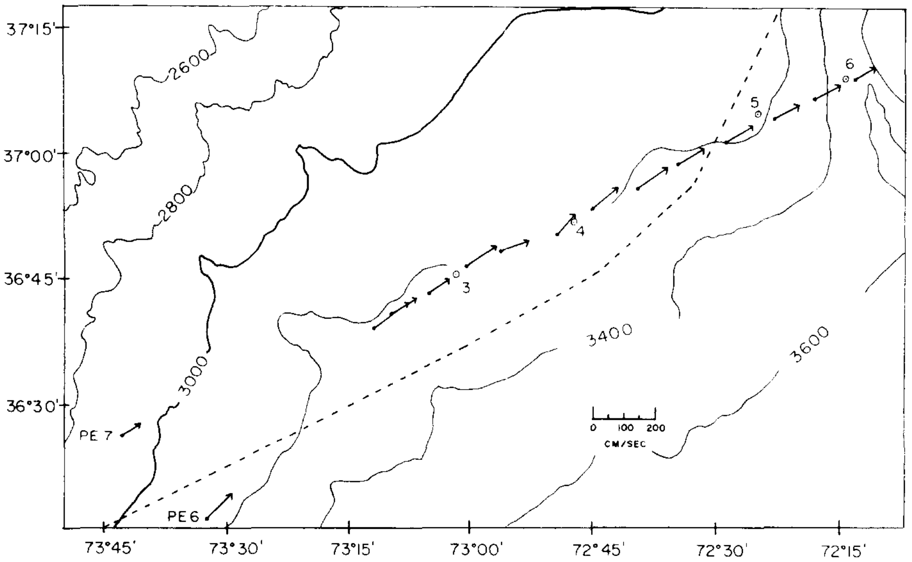

FIG. 3. Float trajectory (. . . .) and velocity relative to the Gulf Stream surface expression, (– – – –), August 1981. Data for the same level from Pegasus stations PE6 and 7 are also shown.

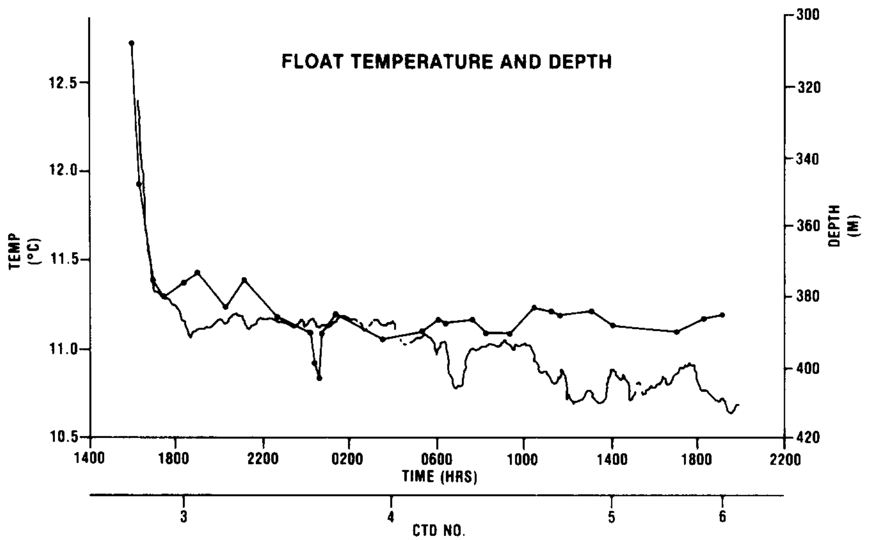

FIG. 4. Telemetered float temperature (curve without points) and acoustically determined depth (curve with points), August 1981.

defined by the 15° isotherm at 200 m (FUGLISTER and VOORHIS, 1965). The float track, near the 380 m level over the 30 hr course of the experiment, indicated by the heads of the velocity vectors in Fig. 3, is remarkably straight for most of the run, with a small mini-meander during the period 2200 August 25–0100Z August 26. Temperature sections at the beginning and end of the track showed that the float maintained its position slightly offshore of the 'core' through the sampling period. The velocity vectors shown in Fig. 3, based on successive pairs of float positions, show reasonable values (on the order of 100 cm s^{-1}) which compared favorably with the acoustically tracked velocity profiler, Pegasus, PE6 and PE7 station values for similar depths.

Time series of float transmitted temperature and acoustically determined depth are presented in Fig. 4. After approximately two hours of settling time, the float showed a decreasing temperature record over the course of the sampling period. The mini-meander transit during 2200–0100Z August 26 corresponded to a depth perturbation of 20 m while temperature was maintained to ± 0.04°C. A subsequent event from 0600–0800Z August 26, depth was maintained to ± 4 m while temperature changed by ± 0.25°C.

Temperature observations telemetered from the float and acoustically determined float depth are compared with the XBT-derived downstream temperature section in Fig. 5. In general, both time series agree with structure in the XBT section, which itself may have depth offsets on the order of ten meters (MCDOWELL, 1977). The systematic offset between float temperature and depth is partly due to overestimating float depth from non-overhead fixes.

The true test of the isopycnal-following character of the float is the density information provided by the Neil Brown Instrument Systems CTD-O_2. In Table 2(a), data taken at the positions shown along the float track in Fig. 3 indicate the variability in sigma-*t* (σ_T) at the acoustically determined float depth. These data were taken within 2 km of the float, and Niskin bottle samples were taken for calibration. During the downstream transect, the CTD data at the float depth showed a slight temperature (0.04°C) and salinity (0.013‰) increase. The σ_T results determined by the above method show that within 10^{-5} density units (gm cm^{-3}) the float tracked the constant density surface $\sigma_T = 27.12$.

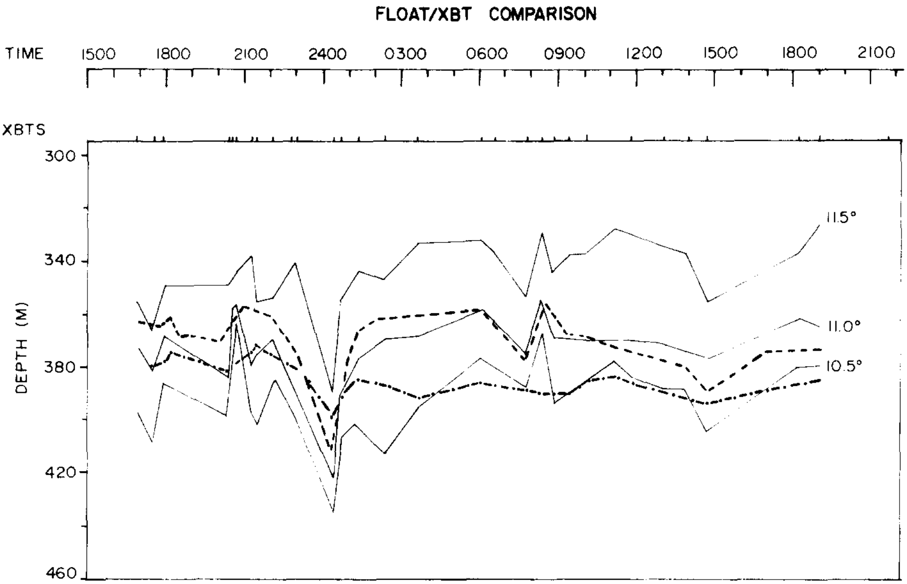

FIG. 5. Telemetered float temperature (°C) (———) and acoustically determined depth (m) (-·-) superimposed on a downstream temperature section from XBT's taken along the float tracks, August 1981.

TABLE 2(a). HYDROGRAPHIC DATA AT THE FLOAT POSITION AND ACOUSTICALLY DETERMINED DEPTH, 1981

CTD#	Date	Time (GMT)	Position	Depth (m)	σ_T
3	8/25	1812	36°41.00'N 73°25.00'W	378	27.12
4	8/26	0327	36°52.00'N 72°47.00'W	391	27.12
5	8/26	1400	37°04.80'N 72°24.80'W	388	27.13
6 ·	8/26	1851	37°08.79'N 72°14.00'W	386	27.13

TABLE 2(b). HYDROGRAPHIC DATA AT THE FLOAT POSITION AND ACOUSTICALLY DETERMINED DEPTH, 1982

Station No.	Date	Time (GMT)	Position	Depth (m)	σ_T
8	9/16	0241	35°48.80'N 74°17.36'W	230	26.74
9	9/16	1422	36°06.97'N 73°48.99'W	275	26.75

The vertical transit of the float determined acoustically [Table 2(a)] is compared to the actual shape of isopycnal surfaces at the CTD stations in Fig. 6. Here the vertical excursions track the σ_T surfaces to a remarkable extent. Also in the figure, the relationship is shown between float depth and finestructure features contained within the oxygen minimum, which was tagged by the float at the start of the experiment. The float is shown within or between local O_2 maxima within the overall O_2 minimum. In CTD Stations #5 and #6, the float may be tagging a local O_2 maximum which itself may be shoaling along the 27.125σ_T surface, suggesting that the float may be used to provide a Lagrangian tag for finestructure.

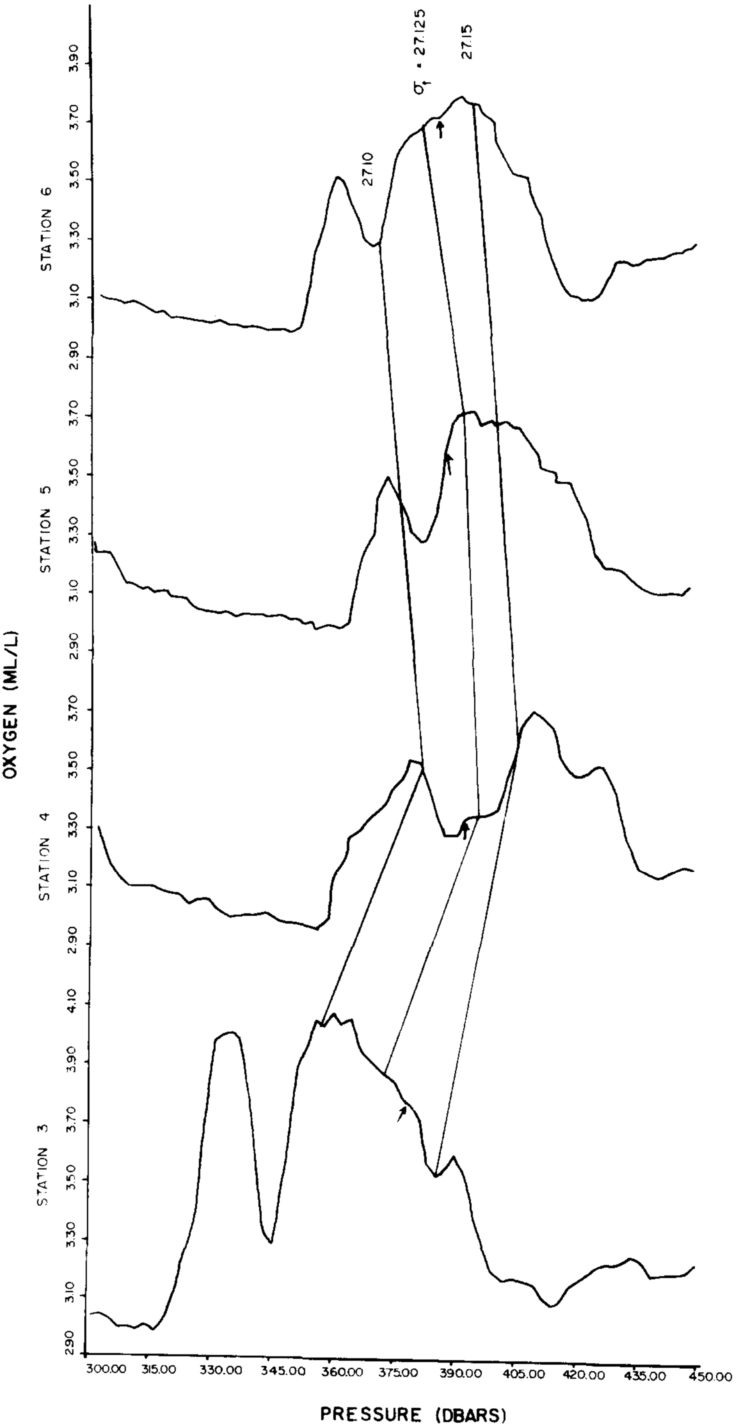

FIG. 6. Float position relative to CTD derived σ_T contours and vertical profiles of dissolved oxygen, August 1981.

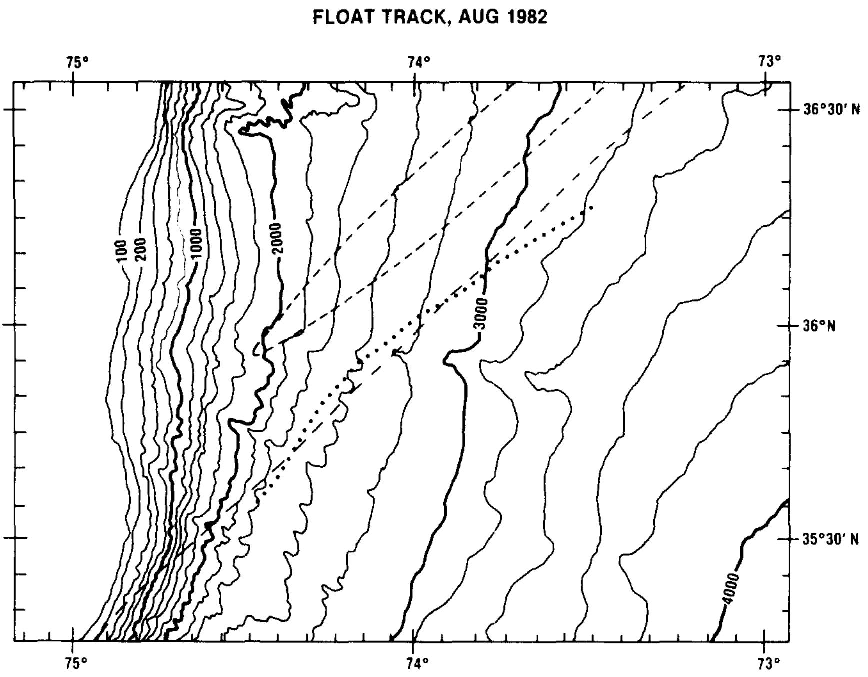

FIG. 7. Float trajectory (. . . .) relative to the Gulf Stream surface expression, September 15, 1982 (– – –). A shingle-like structure to the west connects to the Gulf Stream proper downstream. Data are superimposed on bottom bathymetry (m).

6.2. *September 1982*

The second successful deployment of an isopycnal-following float, a cylindral design previously described, occurred during a 24 hr period on 15–16 September 1982. This experiment demonstrates float behavior in a regime with larger density changes along isopycnals than in the previous run. The float was launched at 35°36.46'N 74°24.48'W (Fig. 7) near the northern edge of the Gulf Stream, as in the previous experiment. The float track near the 250 m level is shown in Fig. 7 relative to the 15 September surface expressions of the Gulf Stream, which itself was moving inshore during the sampling period. The float tracked downstream with a small offshore motion, crossing bottom contours into deeper water. Temperature profiles taken along the track at each float position show that the float remained a few kilometers south of the Northern Edge of the Stream throughout the sampling period.

Time series of float transmitted temperature and acoustically determined depth are presented in Fig. 8. After the initial settling (not shown) the float showed decreasing, then increasing temperature, while its depth increased with time. After the initial temperature decrease which is probably associated with its final approach to equilibrium, the variability of the increasing values were $\pm$ 0.2°C, during a period when the depth increased by approximately 60 m. Near simultaneous records taken at about 74°W by the deep drifter (ROSSBY and DORSON, 1983) near the 400 m level showed the same qualititive picture of increasing depth accompanied by increased temperature, but the accompanying temperature changes were an order of magnitude larger. This illustrates the difference in response of the isobaric (deep drifter) and isopycnal following modes of operation.

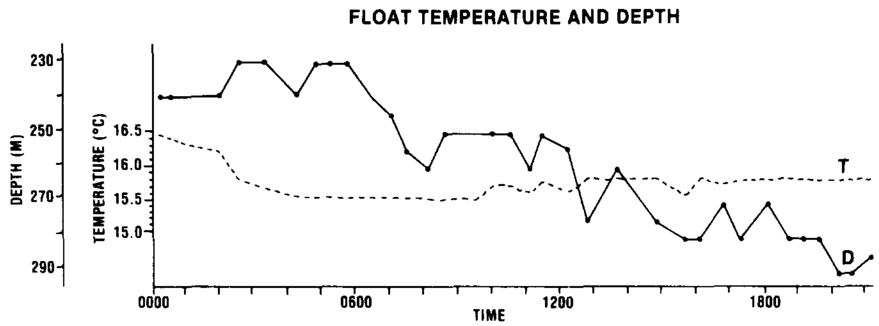

FIG. 8. Telemetered float temperature (---) and acoustically determined depth (-·-) September 1982.

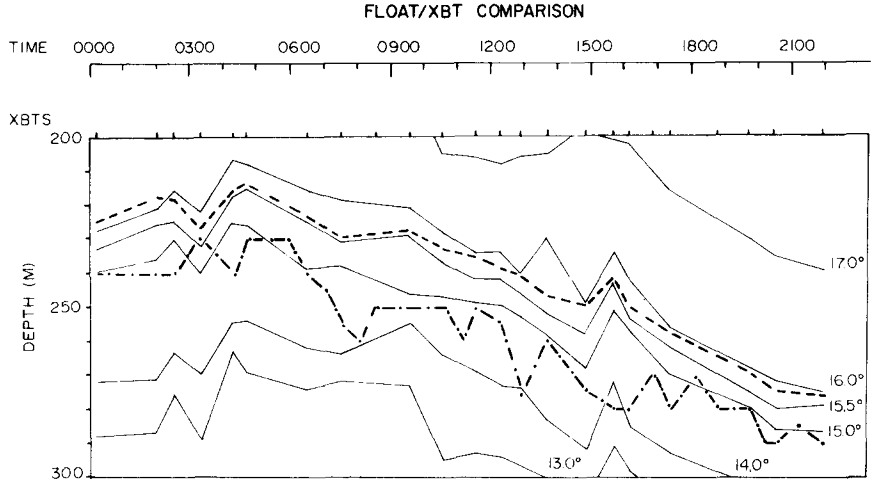

FIG. 9. Telemetered float temperature (°C) (---) and acoustically determined depth (m) (-·-) superimposed on a downstream temperature section from XBT's taken at position indicated in Fig. 7., September 1982.

The 60 m vertical float excursion in Fig. 9 combined with the average temperature gradient in the float depth range, 0.04C°/m would correspond to a temperature change of 2.4°C which is an order of magnitude greater than the observed ΔT. This is even more striking evidence that the float was adjusting depth to maintain its prescribed isopycnal surface.

Temperature observations transmitted from the float and acoustically determined float depth are compared with an XBT derived downstream temperature section in Fig. 9. The float temperature (dashed line) agrees well in curvature with the nearby 15.5° and 16.0° isotherm shapes indicating near-isothermal operation. As observed in the previous experiment, the float depth time series is systematically offset deeper than the float temperature record, probably due in part to errors in overhead positioning.

Once again, a better test of the isopycnal-following character of the float is provided by density data, in this case obtained from hydrostations taken near the float. In Table 2b, data taken from the positions along the track indicates the variability in σ_T observed at the acoustically determined float depth. These data were taken within 2 km of the float; additional stations could not be taken due to deteriorating sea state conditions. In the downstream transect the deepening of the float by 45 m between stations 8 and 9, was accompanied by a temperature increase of 0.06°C and a salinity increase of $0.01^0/_{00}$, compensating to maintain density. The density results show that within ± 10^{-5} gm cm^{-3}, the float tracked the constant density surface $\sigma_T = 26.75$, and thus acted nearly perfectly in an isopycnal manner. In addition, if we calculate density at the float by the second method, pairing float derived temperature with hydrostation salinity (via the observed T/S relationship) the results are equally convincing – with a σ_T range of 26.68 ± 0.01.

7. DISCUSSION

In the two pilot experiments, a simple method has been demonstrated for tracking water parcel motion along isopycnal surfaces. By using a passive mechanical compressee, isopycnal tracking can be approximated. This method exhibits the truest response to perturbations of isopycnals with periods on the order of hours or longer. However, a system whose compressibility exactly equals that of seawater would still not be a perfect isopycnal follower due to a small but finite coefficient of thermal expansion, although this can be reduced by 30% or more by fabricating the compressee from non-metallic materials. In summary, an isopycnal float can be optimized by matching its compressibility to that of seawater, and minimizing its coefficient of thermal expansion as much as possible. In addition, the restoring forces will be maximized and the ballasting errors will be reduced when the float is deployed in a region of strong stratification.

The isopycnal-following Swallow float is an ideal tool for the investigation of a number of upper ocean processs in frontal regions. Using clusters of these instruments along with hydrographic surveys, studies of the topographic effects such as the Gulf Stream departure from the Blake Plateau south of Cape Hatteras, as well as entrainment and subduction processes north of Cape Hatteras can be carried out. In addition to providing three dimensional path information, additional sensors such as oxygen, pressure, and vertical velocity could be incorporated into the system. Multiple float arrays on the same density surface together with hydrographic sampling may permit studies of relative vorticity and its variation in response to topography and curvature along the float trajectory.

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