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Evolution of Lagrangian methods in oceanography

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1.1 Introduction

A complete description of a dynamical system must include information about two things: its state and its kinetics. The first part defines its condition or state at some instant in time, but nothing about its motion. The latter does the opposite, it tells us how the system is evolving, but nothing about its state. Thus, for a full understanding of a dynamical system, we need information on both. If we consider the ocean as such a system, its state would be determined by the distribution of mass while the kinetics of the system would be given by the distribution of currents. Since the birth of modern oceanography, we have developed an increasingly accurate picture of the state of the ocean, more specifically the distribution of heat and salt: the two properties that determine the mass field and hence the internal forces acting on it. Progress has been much slower – and more recent – with respect to a corresponding description of the kinetics of the ocean. Indeed, our view of the ocean circulation is still incomplete and depends to a significant extent upon assumptions about its internal dynamics in order to estimate ocean currents from the observed mass field. We have employed this methodology out of convenience and necessity because for a very long time we did not have the tools to observe the ocean in motion directly.

Fluid motion can be specified in two ways. The first, generally known as the Eulerian method, specifies the velocity field as a function of location and time. The other – Lagrangian – method specifies the position of labeled fluid parcels as a function of time. The two methods have strengths and weaknesses. Virtually all theoretical and numerical research of fluid dynamics uses the Eulerian specification because of the clear separation of the independent variables, space and time. In the Lagrangian frame, the spatial information enters through the initial position of each and every particle. The dependent

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variables are the particles' subsequent positions as a function of time. The equations that describe this system can be solved only for certain, very simple flows, and as a result are hardly ever used. However, from an observational point of view the Lagrangian method has a major advantage in that it tells us precisely how fluid parcels move about in space. This may seem like a self-evident if not tautological statement, but it assumes special significance when one considers how difficult it is to accurately determine the horizontal structure of ocean currents, particularly at depth.

How does one observe the spatial structure of currents and how well can this be done? In the Eulerian frame resolution is set by the number of observation points. In the Lagrangian frame it is set by the number of markers or tagged parcels that are released. For synoptic applications such as tracking weather, the Eulerian specification is the method of choice. The synoptic approach can be very effective in the ocean too but, for a wide range of questions, the Lagrangian approach provides a more natural and cost-effective match. The reason is that continuous tracking of Lagrangian markers allows us to map out the horizontal structure of the flow field in extraordinary detail. Even a single trajectory can be quite revelatory about the underlying fluid dynamics. To illustrate this point, consider a steady flow such as the orbital motion in an eddy. A Eulerian current meter will register a steady flow in a certain direction whereas a Lagrangian marker will immediately paint out the circular structure of the eddy. The technology to study fluid motion in the ocean with Lagrangian techniques has expanded enormously since its birth a half a century ago. In this chapter we review the development of Lagrangian methods for observing ocean currents and how these observations have helped to expand our knowledge of the dynamics of ocean currents.

The development of Lagrangian techniques in the ocean has depended upon two physical properties of the ocean: the existence of an acoustic waveguide and the very low absorption of sound. The waveguide traps sound so it spreads only in the horizontal, cylindrically instead of spherically (acoustic energy decreases as r^{-1} instead of r^{-2}), and the low absorption lets it spread out over great distances. Although it defies the imagination, one can, at low frequencies with special equipment, detect a one-watt sound source at a distance of 1000 km! It is this property of the ocean that permits us to use underwater sound to track Lagrangian markers or floats over wide areas. But this is easy to say now. In fact, the development of the float technology, from the 1950s Swallow float to today's RAFOS float, has depended crucially on the ability to generate low frequency signals to locate and track floats out to distances of 1000s of km. The first section of this retrospective of Lagrangian methods describes the evolution of the acoustic float technology; the second section discusses a range of platform-based *in situ* measurements that have added significant value to the Lagrangian trajectory data. This is followed by a brief review of the sound source technology and acoustic navigation techniques. We then attempt a summary of lessons learned from the use of Lagrangian methods, and the brief last section speculates on likely developments in the near future. Common to the entire discussion given here is the acoustic transparency of the ocean, the property that allows us to generate and detect acoustic signals at great distances for the purposes of location and tracking.

1.2 History of floats

The first neutrally buoyant float designed to track water movements at depth was developed by John Swallow, a British oceanographer. It consisted of two aluminum pipes strapped together with a battery and timer circuit that would excite a magnetostrictive transducer, a “pinger,” hanging underneath (Swallow, 1955), Figure 1.1. The signals could be heard from a ship overhead.

Figure 1.1 This widely reproduced photo shows John Swallow on deck preparing his float for launch. The float consisted of two aluminum tubes strapped together. The toroidal pinger (barely visible to Swallow’s right) hangs underneath. Note the ship’s cat paying close attention!

Using acoustic triangulation the ship could determine the float's position and depth. The weight of the float was carefully trimmed so that it would float at a desired depth. It is also essential that the float be less compressible than seawater. Imagine that for some reason the float is displaced downward a bit. Since it won't compress as much as the surrounding water, it will be lighter than the displaced water and thus return to its equilibrium depth.

The new Swallow float enjoyed great success with the discovery of a south-flowing deep western boundary current (Swallow and Worthington, 1961) that had been predicted by Stommel (1957). The direct observation of southward motion of several floats was far more convincing than estimating currents from geostrophy given knowledge of the density field, also known as the dynamic method which yields only relative and not absolute velocity information. Steele *et al*. (1962) used Swallow floats to confirm and estimate the deep transport out of the Norwegian Sea south of Iceland. The Swallow float was also used to study deep flow west of Bermuda. The premise had been that the currents would be rather weak revealing the interior broad scale abyssal circulation required to balance the rapidly flowing deep western boundary flow. Instead, very energetic mesoscale motions on time scales of a few weeks were observed, precluding any accurate estimate of the mean circulation at depth (Crease, 1962). It was perhaps this study more than any other that alerted oceanographers to the existence of an energetic deep ocean. But it also made clear the prohibitive cost of tracking floats for any length of time on the high seas from surface vessels. Swallow (1971) reflects on those early observations.

It had been known for some time that sound can propagate great distances through the ocean and that this acoustic "transparency" of the ocean could be used to track subsurface drifters. Stommel, in a letter to the editor in Deep Sea Research in 1955, proposed to deploy subsurface drifters that would be located from time to time by generating explosive signals that would be picked up at distant hydrophones (underwater microphones) using the acoustic wave guide, usually known as the deep sound or SOFAR (SOund Fixing And Ranging) channel (see next paragraph). Stommel had in mind a float that would release a small explosive device that would detonate when it had reached a certain depth or pressure. At the same time it would release a compensating buoyant element so that the float from which these were released would remain at the same depth as it continued to drift. Actually, he touched on the idea of using floats in an earlier paper (Stommel, 1949) where he suggested using the SOFAR channel to study eddy diffusion in the ocean – the dispersion of fluid parcels – on the gyre scale. Nothing came of these ideas at the time, but they did highlight the potential for using the SOFAR channel for tracking subsurface drifters over

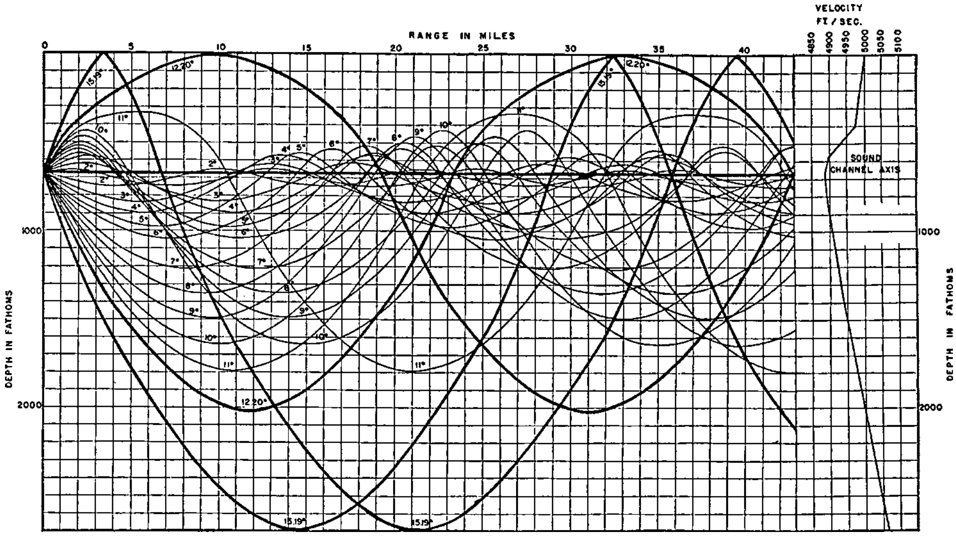

Figure 1.2 Ray diagram of sound propagation through a stratified ocean showing both refracted and surface reflected rays (from Ewing and Worzel, 1948).

great distances for extended periods of time. These early ideas remained on his mind, as we shall see.

The SOFAR channel was discovered during World War II at the Woods Hole Oceanographic Institution as part of its research into the acoustics of the ocean, a very important aspect of antisubmarine warfare (Ewing and Worzel, 1948). The SOFAR channel is an acoustic waveguide due to a sound velocity minimum below the warm upper ocean. The speed of sound is a positive, nearly linear function of both temperature and pressure such that the speed of sound first decreases with increasing depth due to the rapid decrease in temperature. Beyond a certain depth below which temperature only slowly decreases, the pressure effect dominates such that the speed of sound increases with further increase in depth. This minimum in sound speed, typically about 1490 ms^{-1} around 1000–1300 m below the surface in tropical and subtropical waters, gives rise to a sound channel which tends to trap sound near these depths, in short an acoustic waveguide. Figure 1.2 (widely reproduced from the 1948 Ewing and Worzel paper) illustrates the trapping of sound in the sound channel.

In 1965–1966, at Stommel's initiative, M. J. Tucker, on sabbatical leave from England at the Massachusetts Institute of Technology, and Douglas Webb at the Woods Hole Oceanographic Institution (WHOI), used a low frequency piezoelectric transducer, small enough for neutrally buoyant float applications, to evaluate its use for acoustic signaling in the SOFAR channel (Webb and Tucker, 1970). It was tested from the RV Chain in early 1966, Figure 1.3. The transmissions from the transducer could be detected at a hydrophone at sound channel depth (~1200 meters) at Bermuda 270 km away. This was a major breakthrough for it confirmed that purposeful acoustic signaling from lightweight transducers over hundreds of kilometers in the ocean was possible. Questions remained about the attenuation of sound in the ocean, i.e. how far one could transmit, but this was a crucial first step.

Later that year (1966) the author joined the Stommel/Webb initiative to develop and deploy a first long-range Swallow float or SOFAR float as it came to be known. The first one was deployed in January 1968 and could clearly be heard at 846 km distance. Specially designed signal detection and recording equipment using existing SOFAR hydrophones at Eleuthera (in the Bahamas), Puerto Rico and Bermuda had been set up to listen to and track the float. Figure 1.4 shows the first signals received at Bermuda. Note the roughly five second spread in the arrival of each 1.4 second long signal reflecting the early arrivals of the off-axis rays first (the path is longer but the average speed of sound is greater) and the more solid last arrivals due to the concentration of rays closer to the sound channel axis. Unfortunately, the float failed after only one week. A second deployment a few months later lasted only 2 days. After a substantial redesign effort, a third float was deployed in October 1969 and was tracked for four months before it failed. One possibility for the first two failures may have been that the cables, which hung loosely between the aluminum sphere and the transducer, were vulnerable to biological attack (fish bite). Although this was only a guess, the float was redesigned to make it more rugged, Figure 1.5. The transducer sits inside an oil-filled white polypropylene boot only the top part of which is visible in the photograph (due to the protective frame used for deployment).

In parallel with the SOFAR float work, the author explored other approaches to estimating currents from 2-point displacement vectors, i.e. from knowing the start and end points only. These would give us mean flow patterns at much lower cost albeit without any spatial or temporal detail along the trajectories. Ensembles of mean displacement vectors would nonetheless provide independent information on the mean circulation at depths where the dynamic method gives little insight. Building upon Stommel's original idea of using small explosives to study currents, but instead of a single float carrying many charges, we used many small floats, each one with a single pressure-actuated explosive. The charge was a standard SOFAR signaling device secured inside a small glass flotation sphere. The sphere float had a small port to allow it to be flooded at a certain time. This would cause it to fill until

Figure 1.3 Gordon Volkmann (left) with acoustic transducer about to be lowered to sound channel depth to test long-range transmission through the ocean. The ring transducer visible below the shiny electronics module operated at 778 Hz.

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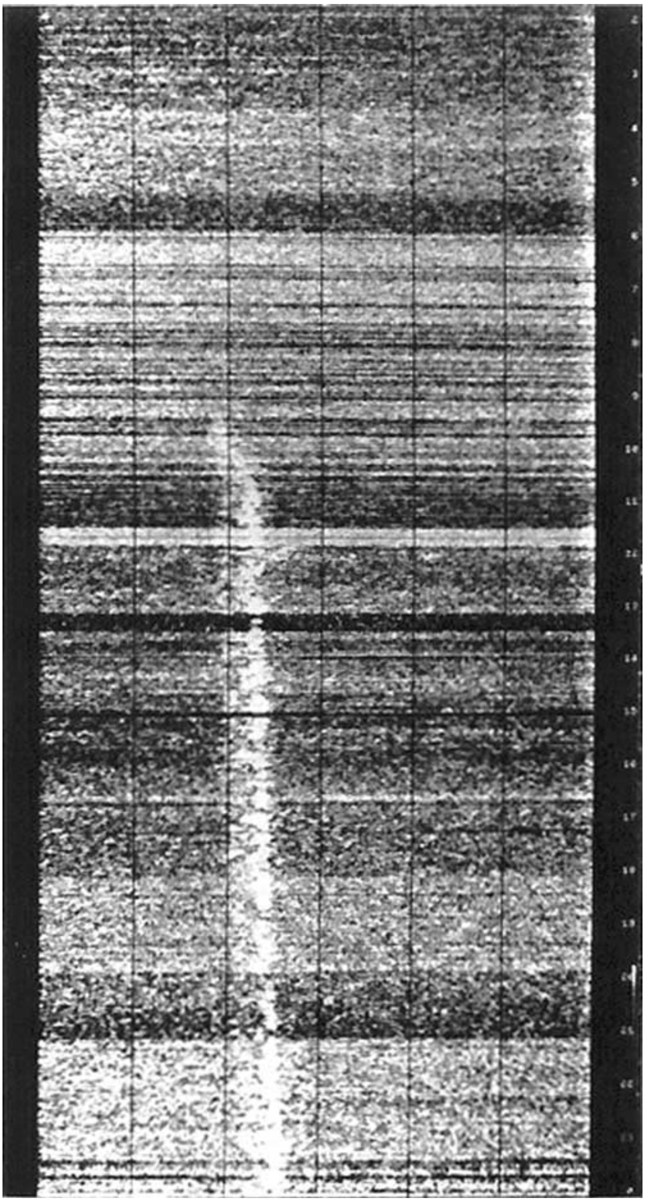

Figure 1.4 Visual display of first signals at Bermuda from SOFAR float #1 January 20, 1968. The scales are 1 minute across and 0–24 hours top to bottom. The bright line shows the one per minute transmissions starting at 0930 GMT. At first only the early off-axis arrivals show up because the float has just been deployed and has not yet reached sound channel depth (Rossby and Webb, 1970).

Figure 1.5 The aluminum sphere SOFAR float with the transducer underneath (mostly concealed by launch frame). See Plate 1 for color version.

the pressure reached the point where the charge was hydrostatically armed and subsequently triggered. An exploratory experiment to test the concept took place with a dozen floats set to drift for three weeks. Unfortunately, due to a leak in the flooding mechanism only one displacement vector was obtained. While the test showed that the concept did work and could have been improved upon, working with explosives, although small and safe, held little appeal for further use.

1.2.1 The SOFAR float

Regardless of the reasons for the short life lengths of the first generation SOFAR floats, it became clear that the high cost of fabrication of the machined aluminum flotation sphere and the piezoelectric transducer hanging underneath would preclude their use in large numbers. To address this, Doug Webb suggested using a resonating tube instead. It would be excited by means of a thin piezoelectric bender plate at the closed end of the tube, the length of which would be carefully trimmed to achieve resonance at the desired operating frequency. Instead of using spheres, flotation would be provided by commercially available extruded aluminum tubes cut to the appropriate length. True, the floats were much larger than the compact spheres used earlier, but this could be countered by the use of suitable handling tools. The first design, Figure 1.6, had two resonator tubes, one to each side of the center flotation tube. Later, a single tube was mounted end-to-end to the main tube, Figure 1.7. These instruments proved enormously successful. They enjoyed their first major use in the Mid-Ocean Dynamics Experiment (MODE) in 1973. Twenty floats were deployed at a depth of 1500 meters. They could be called to the surface acoustically by sending a command to drop a small ballast weight. This proved valuable for many of the floats had to be recovered and repaired due to small leaks to the oil-filled bender plates. But the repairs could be completed at sea, and the floats performed admirably thereafter. Numerous studies have been written using these data. The data are described in detail in a technical report (Dow *et al.*, 1977) and two papers (Rossby *et al.*, 1975; Freeland *et al.*, 1975) provide a first synthesis of the observations. This was the first study to use coherent arrays of floats to study sub-mesoscale dynamics.

1.2.2 The mini-MODE float

Another very clever Lagrangian contribution to the MODE consisted of the mini-MODE program (Swallow *et al.*, 1974). These floats were transponding