An Account of the Usefulness of New Techniques of Measurement in Study of the Gulf Stream

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INTRODUCTION

Over the past 50 years our knowledge of the Gulf Stream has grown by recognition of new theoretical ideas, innovative analysis of existing data, and the introduction of new technology of measurement. At any particular time the total body of knowledge has been so incomplete that it has never been possible to design an overall strategy of Gulf Stream exploration. Even today it seems that we still must proceed by a process of trial and error, finding our way, step by step, as new problem areas open up. The purpose of this article is to illustrate how the introduction of new instruments has led to a growth in knowledge of the Gulf Stream, often in unexpected directions.

MEASUREMENT TECHNIQUES

Bottle Station

Systematic study of the Gulf Stream in the 20th century began in 1930 with the acquisition of the ketch ATLANTIS, its deep-sea winch, and an array of reversing thermometers and sample bottles. Positions were determined by celestial navigation, weather permitting. This technology was sufficient to obtain the rather widely spaced station data that enabled Iselin [1] to work out a zero order designation of water masses in a physical-geographical study of the circulation of the Western North Atlantic. The picture was broad brush—it was not in any sense synoptic, put no limits on the range of temporal variability, and did not resolve well narrow features like the Gulf Stream frontal structure. Nevertheless it gave the first good idea of the general setting and environment of the Stream and revealed the sharpness of the T-S relation in this part of the ocean. The ATLANTIS was small enough for its operation to be limited by bad weather, but a larger all-weather vessel would have been beyond the means of the Institution, and the first director, Henry Bigelow, considered $15 a day an outrageously large fuel bill. Iselin's assistants then embarked upon a Montauk Point to Bermuda quarterly shuttle [2] with the hope of obtaining a good picture of the variability of the Stream. When successive sections made during these shuttles showed what appeared to be multiple crossings of the Stream, the idea of meanders was not invoked. It was even advanced that large features, which we now would recognize as cold eddies, were large solitary internal waves. A determined effort to observe internal waves while drifting (near 34°N, 66°W) was made on the R.V. ATLANTIS when 193 consecutive hydrographic stations were obtained between June 16 and June 29, 1938. The result was disappointing—no huge internal waves (with hoped for amplitudes of hundreds of meters) passed by the ship. H. Seiwell, who initiated the project, did not write it up.

Any attempt to make a fine scale survey of the Gulf Stream front was frustrated by spotty navigation, inability to discover the direction of drift of the ship, and to some extent the awkwardness of trying to use hydrocasts (with all the time consuming reading of thermometers, calculation of thermometer depths, and large wire angles) in a running mapping survey. The interpretation of the quarterly sections was, accordingly, not very revealing—and results of the attempt to extract evidence of annual variability of the Stream (with the exception of the marked seasonal signal in the mixed layer) were ambiguous. The outset of World War II threw into disarray the plans to operate a second ship (the CULVER) on a year round schedule near Bermuda.

LORAN and the BT

The two important technical developments during the War that gave rise to a realistic chance to map the Gulf Stream front—and indeed to discover meanders and eddies—were the smoked-glass-slide bathythermograph and LORAN. The BT was cheap, fast, and usable in fairly bad weather and while underway. Directly south of Woods Hole LORAN gave positions continuously to about ½ nautical mile accuracy. Its coverage further downstream toward the Grand Banks was not nearly so good. These two tools were used to portray the finer structure of the Stream in all its complexity—the twists and turns of the current, its narrowness and intensity, the puzzle of eddies and meanders—and to determine how these evolved with time.[3] The research vessels used—several even smaller than the ATLANTIS—were so slow that the investigators evolved a zig-zag search pattern, moving downstream because the ships could not have made much way against the Stream.

Towed Instruments

The multiship Operation Cabot of 1950[4] was designed to survey a larger area than previously possible, and succeeded in mapping a long developing cold eddy, breaking off from the loop of a meander. That is, Gulf Stream Rings were discovered. Ford, Longard and Banks[5] also used their continuously monitoring temperature and salinity probe, which was towed near the surface. It revealed some of the fine salinity structure on the north side of the Stream—there seemed to be filaments or threads of fresher slope water entrained into the Stream near Hatteras. Their instrument was successfully used as a guide to steaming along the Gulf Stream front in the so-called McNulty experiment on the NEW LISKEARD in 1949.

The GEK[6] was also developed at this time. It was capable of giving good estimates of surface velocity which were helpful in deciding which way the instantaneous current was flowing across a BT section—and proved helpful in mapping surveys. This was particularly useful in ocean regions where LORAN was not available, and played an important role in the postwar Japanese studies of the meander and loop structure of the Kuroshio.

Von Arx, Bumpus and Richardson[7] successfully exploited the GEK and BT on board CRAWFORD in 1958 by repeatedly occupying a section across the Gulf Stream south of Cape Hatteras for the period of a month, and from these data they were able to map out an asymmetry of meanders there which they called shingles. Webster[8] analyzed the surface current field from the GEK data of this CRAWFORD cruise to obtain an estimate of the eddy momentum flux u'v' and found the surprising result that surface momentum was flowing eddywise into the Stream, not away from it.

The success of Fuglister's mapping studies stimulated development of other technologies, not all as successful as the BT/LORAN combination. Malkus's bathypitotmeter was unpopular because it did not read direction, the tapes were troublesome to read, and they required the presence of the inventor or his assistant to ensure proper operation.

Fuglister[9] developed a way of using a towed V-fin at 200 meters to follow the axis of the Stream from a moving ship, and persuaded the Coast Survey to undertake a series of voyages for over a year. These studies, written up by Hansen,[10] showed a downstream progression of meanders. The method was found to be impractical in the Kuroshio because of the interference of large numbers of long lines in which the V-fin tangled.

The towed thermistor chain was a technological development that had minimal impact on Gulf Stream studies, and from which little was learned. Heavy, one of a kind, with uncertain calibration and wandering depth scale, and installed on a ship dedicated to geology and geophysics, it was essentially unavailable to physical oceanographers.

The Fuglister strategy of BT/LORAN, supplemented with current indication from the GEK, led, instead, to the possibility, once the direction of the current was known, of steaming on the wire, and getting deep reversing-bottle casts in the current. Starting in 1950 with his three classic sections, Worthington[11] finally succeeded in getting casts all the way to the bottom. These revealed a major feature: the slopes of the isotherms and the isohalines extended all the way to the bottom. This was quite a surprise to those who thought of the Gulf Stream as part of a wind-driven circulation limited to the depth of the thermocline.

Lowered Current Meters

Unfortunately it was not technically feasible to measure these deep sub-Gulf Stream flows by lowered current meter. Over the years several had been developed for lowering on a wire: the old Ekman model, and variants by Malkus[12] and von Arx.[13] These might work in a river or even a lake, but when lowered from a drifting and pitching ship at the end of a long wire in the Gulf Stream, no one could expect to interpret the readings meaningfully, nor could long enough time series be obtained to be sure of their representativeness of the long term mean.

Airborne and Satellite Infra-Red Thermometry

Stommel et al.'s[14] airborne radiation thermometer foundered because of the need to have aircraft available on a daily basis, and because the somewhat doubtful temperatures recorded were ocean surface temperatures—those beneath the surface could sometimes be very different.[15] It was soon obvious that a small, slow surface vessel could outperform aircraft. It could stay in the area for weeks at a time, and it could get subsurface measurements. There really was no contest between the airplane and the surface ship: it was a classic example of the hare and the tortoise. In recent times, when satellite borne infra-red measurements have become commonplace the large field of view has revealed many interesting features. But there is still reason to question how representative they are of deeper structural features of the Stream and its environs. Halliwell and Mooers[16] used satellite images to obtain statistics on position, variance in location and wavelengths of meanders.

Swallow Floats

The first hope of determining the direction and strength of the deep flow under the Gulf Stream gleamed when Swallow[17] demonstrated the feasibility of building and tracking neutrally buoyant floats in the deep ocean. Meanwhile Worthington had made a section off Cape Romain that showed the Gulf Stream up against the continental slope, and the deep isothermal slopes displaced seaward. This seemed to be an excellent place to do some float tracking, because the ship could operate seaward of the strong surface currents. The DISCOVERY II and ATLANTIS conducted a joint float tracking and hydrographic study off Cape Romain in 1957,[18] and unequivocal evidence of a deep countercurrent was found. Subsequent tracking exercises in other portions of the Stream by Fuglister,[19] Barrett[20] and Volkmann[21] showed that more often the deep floats moved in the downstream direction of surface current. It was obvious that the need for a mother tracking ship was so restrictive that a satisfactory program to map deep currents would require something else.

The requisite technology again appeared: moored current meters and SOFAR tracked floats. The earlier float experiments were very important in stimulating these developments. They showed that there really are strong currents at depth and that a deep moored current meter or float would not simply remain stalled. And some very interesting results were also able to be obtained by free falling profilers. But before turning to an account of these developments, and how they were used to tell us more about the Gulf Stream, we should say a few words about these present day descendants of the water bottle and BT: the STD/CTD and the XBT.

The CTD and XBT

Both of these and their support equipment are much more expensive than the old technique. Both mean less time must be spent on deck—and have bred a new generation of dry-footed oceanographer. The idea of throwing over the side something equivalent in cost to a gallon of whiskey for each XBT lowered is now routinely acceptable. The main advantage of the XBT is that it goes much deeper than the old BT.

The XBT has been used creatively in some mapping exercises, during which it obtained synoptic maps of the Gulf Stream path, size, shape, and movement of Gulf Stream Rings, on both sides of the Stream. The CTD is more ponderous: it comes with a computer and computer-operator. Despite the state-of-the-art data processing and graph plotting capabilities it is rare that the data is reduced in final form when the ship reaches the dock—as it used to be in water bottle days.

As useful as it may be for other problems in oceanography, the CTD does not seem to have produced critical new knowledge of the Gulf Stream, although it has added a great deal of information.

The multiship survey "Gulf Stream 1960" consisted of three phases.[19] The first phase was a regular set of parallel hydrographic sections, made just before the introduction of the STD—it does not seem likely that the interpretation of this very substanital set of data could have been improved much had the STD been available then.

Moored Instruments

In the late 1950s W.S. Richardson had begun to experiment with building moorings and current meters to go on them that could be deployed for long times in the Gulf Stream. It was a slow process—and in the early stages there were many problems: the choice of sensors, the methods of recording, tactics of sampling and data processing, calibration, mooring and instrument design, and quality control. It took ten to fifteen years of unremitting effort on the part of the W.H.O.I. buoy group to develop a system that could be used routinely. Because of the strong currents anticipated in the upper levels of the Gulf Stream it was decided to carry out the first fairly elaborate array experiments in regions north and south of the Stream, and only at the deeper levels in the vicinity of the Stream itself.

In the early 1960s, problems in maintaining moorings with a surface appendage in the ocean (anywhere), especially near strong currents like the Gulf Stream, led to developmental efforts with (presumably simpler and easier) near-bottom moorings. The first attempts of this type in the mid-1960s were partially successful, mostly restricted to short deployments. The earlier data were dense in time, but of short duration, and consequently the first results were on phenomena with relatively high frequency.[22,23,24]

Development of a working acoustic release (late 1960s) and quality control procedures (early 1970s) led to routine, long-term, near-bottom moorings in the vicinity of strong currents (as well as otherwise). The first operational deployments[25] of large arrays of the resulting system were in 1973-1975.[26,27]

The successful near-bottom mooring became the prototype for extending measurements farther up into the water column. These "intermediate moorings" were initially exploited during the mid-70s in weak current regimes away from the Gulf Stream System. The first long-term moorings reaching up to the thermocline in the immediate vicinity of energetic segments of the Gulf Stream System were deployed and recovered in 1975-1977 (POLYMODE Arrays 1 and 2).[27,28,29,30]

However none of the POLYMODE moorings were set directly in the "upper levels" of energetic regions of the Gulf Stream System. In 1979, moorings were set with instruments up into the thermocline in a less energetic region (Grand Banks) of the Stream, and recovered after more than a year's exposure with no major problems. The first long-term mooring extending above the thermocline in an open ocean mid-latitude jet was in fact deployed in the Kuroshio System in 1980 (and recovered in 1981).[31] An upper level mooring in an energetic segment of the Gulf Stream was just set for the first time in late 1982 and recovered in 1983.

The data obtained by moored current meter averages have been essential in establishing reliable estimates of Eulerian mean currents in the vicinity and under the Stream. This work began with the results by Schmitz, Robinson and Fuglister[25] based on data obtained from a few near bottom moorings under the Gulf Stream. Since then Schmitz[27,29,30] in a series of papers, has estimated long term means which delineate some features of the latitudinal dependence of the deep mean currents, and this is the primary independent evidence for the reality of the recirculation hypothesized by Worthington. Various statistics have also emerged from the cross-stream arrays: eddy-kinetic energies, momentum transports, correlation distances, etc. Luyten,[26] Owens et al.,[32] and Bryden[33] have also studied data from current meter arrays in and near the Gulf Stream. The current meter data has taken its place beside hydrographic station data as one of the main techniques and sources of data describing the Gulf Stream System. Generally speaking, however, moored current meter data have been more influential in studying the eddy field than the general circulation.[34]

Variations in acoustic travel time of a signal emitted from a bottom-moored echo sounder (inverted echo sounder = IES) are a measure of the variations of vertically integrated density in the water column. Watts and Johns[35] have successfully obtained a year's record from three IES pairs bracketing the Stream at sections spaced 50 km apart downstream from Cape Hatteras. These data are not interrupted in time, as the infra-red satellite images are by clouds, and from them Watts and Johns have been able to determine empirical dispersion curves and growth rates at higher frequencies than was possible before, and to argue that the driving mechanism of the meanders in this portion of the Stream is baroclinic instability.

Free Fall Devices

The development of the free fall transport floats[36] made it possible to obtain a statistically significant measure of the mean and time variability of the total transport through the Florida Straits[37] and to some extent on the Blake Plateau[38]—perhaps the only quantitative direct measurement of the mass transport of any segment of the Gulf Stream System that we have. Knauss[39] and Barrett and Schmitz[40] initially extended these techniques to Cape Hatteras and beyond. In retrospect it now seems that the potential of this technique, and of using some of the descendent devices like the acoustic profilers, to obtain representative transports and velocity profiles across open ocean sections of the Gulf Stream could have been more fully exploited. The temporal and spatial sampling problems accelerate dramatically downstream. Rossby has recently begun to make systematic profiler studies of the Stream.[41]

Drifters and SOFAR Floats

In the 1960s, drogued drifting buoys with radiotransmitters were tracked by Fuglister[19,42] from ship and airplane. The buoys followed surface currents in Gulf Stream rings and were useful in following their movement and giving surface velocities. Later, Parker[43] described some buoys tracked by ship in the high velocity part of the Stream which gave some first long term trajectories of the Stream. He made concurrent subsurface measurements and concluded that the buoys closely followed the subsurface thermal front for distances greater than 1000 km. Speeds up to 5 knots were encountered and decrease of speeds toward the east was discovered. Tracking larger numbers of buoys over larger areas for long periods of time became possible in the early 1970s with polar orbiting satellites. During the 1970s a sufficient number of buoys were tracked in the Stream to give qualitative and quantitative estimates of Gulf Stream paths and the influence of seamounts, surface current variability, and movement of rings.[44,45,46] Buoy trajectories were combined with satellite IR thermal maps and occasional AXBT surveys to reveal synoptic scale features of the Stream.

A disadvantage of surface drifters was that they were located in the wind-driven mixed layer and were influenced to an unknown extent by waves and wind on the hull. SOFAR floats, as developed by Rossby and Webb,[47] provided a nice solution to these limitations and gave the first measure of long term quasi-Lagrangian trajectories of water parcels and their dispersion in the ocean.[48] Earlier, in the 1960s, Fuglister,[19], Barrett,[20] Warren and Volkmann[49] tracked swallow floats for short periods of time in the Stream. The interesting but rather erratic behaviour of these floats suggested that much longer trajectories were needed. The use of SOFAR floats in the Gulf Stream required two developments: (1) a long lived float that could be heard over long distances and through varying water masses, and (2) a moored self-recording listening station that would eliminate the geographical constraint of shore stations which were primarily located along the Antilles. These were developed by Webb, Bradley and Valdes at Woods Hole in the late 1970s. In 1980 the first array of SOFAR floats was tracked in the Gulf Stream entirely by means of moored listening stations.[50,51] The trajectories graphically showed the convoluted paths that water parcels follow within the Gulf Stream System. Floats deployed well below the main thermocline were carried directly across the mean axis of the Stream into the less energetic water on both sides. A sufficiently large number of float trajectories have been (and are being) accumulated in the Stream that statistically significant summaries are now being prepared.[50,52,56]

SOME NEW POSSIBILITIES

Today there are new techniques waiting in the wings that should, when imaginatively and energetically applied, add new knowledge to our understanding of the Gulf Stream: in particular, satellite altimetry and acoustic tomography. The properties of these measurement systems have been fully described and discussed elsewhere.[53,54,55] We recommend that these new methods be exploited and feel that they will be successful in a variety of oceanographic problems. Whether these particular measurement systems should be the next major wave in Gulf Stream studies awaits the inscrutable future. We have tried to indicate in this article that there is considerable historical precedent and practical reasoning behind the idea that the first trials of their usefulness ought to be comparatively modest experiments. We also feel that satellite altimetry and acoustic tomography should not be used to the exclusion of other techniques that have proven useful, and in the last analysis would prefer to evaluate not technology alone but the ideas that are to be examined. A trial of these two new technologies in the Gulf Stream for several years could help oceanographers determine what kind of role they can be expected to play in the evolution of future experiments.

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