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OCEAN CURRENT MEASUREMENTS: CHALLENGES AND OPPORTUNITES IN THE FLORIDA CURRENT

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ABSTRACT

The Florida Current flowing along the southeastern coat of Florida is one of the fastest ocean currents on the globe, transporting vast amounts of water and heat from the lower latitudes to the north. This flow consists of strong eddies and other rotational components generated by its passage around the tip of Florida and its dramatic change in direction from east to north up the Florida Straits. Measuring this variability has been a challenge for well over 100 years, and the resulting dataset is an invaluable resource for modern oceanographers. An understanding of historical equipment and methods as well as the evolution of modern devices is essential for the informed planning and execution of detailed measurement efforts in the challenging waters of the Florida Current. This document provides a review of historical and modern equipment that may enable the measurement of the highly dynamic surface waters of the Florida Current and provide insight on short-term variability and turbulence, as well as information beneficial to new technologies such as ocean energy production and environmental issues including global warming.

Keywords: Gulf Stream, instrumentation, ADCP, ocean current, Florida Current, geostrophic intensification, CODAR, SNMREC, technology review

INTRODUCTION

The water velocities offshore south Florida are dominated by the Florida Current, and these effects result not only from the tremendous flow of water between Florida and the Bahamas, but also from the eddies and other rotational components imparted by the change in flow direction from eastward to northward along the Florida Keys and the end of the peninsula. These currents have been measured for decades, with methods ranging from subsurface floats to acoustic Doppler current profilers (ADCPs) and surface current measuring radars. Data suggests that there is a large degree of variability in the mean flow, including significant vorticity events, yet a comprehensive measurement, characterization, and model validation effort of the small timescale variances (hours to days), also known as turbulence, has not been conducted to date.

In addition to local effects, the Florida Current has long been of interest because of the central role it must play in the general circulation of the North Atlantic Ocean and its probable role in global climatology (Leaman et al. 1987). Studies have indicated that advection of heat by ocean currents plays a major role in determining climate. The Florida Current is known to be a major transport system for heat flux across 25° N, an important location in the meridional transport of heat in the subtropical gyre (Molinari et al. 1985). Logistically the Florida Straits have always been attractive to study because it is geographically constrained by the Florida Peninsula and the Bahamas. More recently, the potential for producing a source of clean and renewable base-load power for the Southeast Florida metropolitan area utilizing the current has been proposed (Van Zwieten et al. 2013). Because of these reasons, the Florida Current has been one of the most studied ocean currents for well over 100 years.

The large number of historic measurements provides an opportunity to verify computer models thru hind casting and supplement ongoing measurement and modeling activities. These datasets not only provide historic data at specific times and locations, but also depending on correlation between historic and contemporary measurements, may enable information on climatological trends to be inferred without requiring additional measurements.

Past studies utilized a wide range of instruments, from mechanical current meters in the late 1800's to modern acoustic and radar based systems at the leading edge of modern technology. The advantages of various sensors, as well as their limitations in certain applications, provide guidance on the proper means for additional data collection. A comprehensive review of historical equipment as well as the evolution of modern devices is essential for the informed planning and execution of detailed measurement efforts in the challenging waters of the Florida Current.

An impressive amount of invaluable time series data on the transport and variability of the Florida Current has been collected, and most studies focused on mean transport values for the entire volume passing through the Straits of Florida. Due to technical considerations or equipment limitations, most measurements have been made only within about 150 meters of the surface near the core for any extended periods of time (Lee et al. 1985, Johns and Schott 1987, Hamilton et al. 2005). Dropsondes and surface-moored measurement efforts have investigated the shallow upper portion of the current, but again focused on longer-term average behaviors (Schmitz and Richardson 1968). Modern technology, such as acoustic profiling devices and surface current radar systems, as well as targeted use of more established point measurement devices, may enable the measurement of the highly dynamic surface waters of the Florida Current and provide insight on short-term variability and turbulence, as well as information beneficial to new technologies such as ocean energy production.

1. OCEAN CURRENT OVERVIEW

1.1 GENERATION OF OCEAN CURRENTS

Currents are often regarded as "rivers in the sea", although they are more multifarious than any river system. The spatial and temporal variations in velocity are more complex than could ever be shown by the most detailed series of contemporary current charts (Colling 2004). The ocean currents are complicated because, superimposed upon the major currents that transport enormous masses of water, there are irregular eddies that may reach to great depths, wind currents that are confined to the surface layers, and tidal currents or currents associated with internal waves which are present at all depths but change periodically (Sverdrup 1970). While mean flows seem consistent as rivers, the dynamic variations at temporal scales from minutes to years is extremely complicated and poorly understood. General flow behaviors, however, lend themselves to theoretical explanations.

Ocean currents are generated by two primary forces, differences in the density of adjacent water masses, which in turn creates a potential force between areas of low density (lighter water) and areas of high density (heavier water), and the action of surface winds. The density variation produces a horizontal pressure gradient (HPG). This gradient tends towards equilibrium by the horizontal movement of water from areas of higher pressure to lower pressure. These HPGs generate a sea surface slope, with lines of equal pressure, or isobars, sloping from areas of high to low pressure (Stommel 1965).

In a non-rotating fluid, water would tend to flow from the higher pressure locations to the lower pressure areas, ie. "downhill", but in a moving fluid rotational effects also influence fluid motion. The Coriolis Force (*CF*) is a "virtual force' imparted upon a fluid due to the rotation of the earth, and causes a moving fluid to be steered to the right of the flow direction in the Northern Hemisphere, and to the left in the Southern Hemisphere (Stommel 1987). The *CF* varies as a function of latitude, from zero at the equator to a maximum at the poles. The magnitude is given by:

$$CF = m \times 2\,\Omega \sin\phi \times u \qquad (1)$$

where

m = object mass (kg)

Ω = earth's angular velocity (7.29×10^{-5} s^{-1} at the poles)

ϕ = latitude (deg)

u = object velocity (m/s).

The quantity $2\,\Omega \sin\phi$ is also known as the Coriolis parameter and is designated as f, so the equation becomes $CF = mfu$.

Since the latitudinal, or zonal, location of an object on the earth's surface rotates about a smaller radius from the axis of the earth the higher the object's the latitude, but angular momentum must be conserved, the object changes speed relative to the surface of the earth as it moves between different latitudes. The equation for angular momentum (L) is:

$$L = m \times r \times \omega \qquad (2)$$

where
m = object mass (kg)
r = radius from the earth's axis of rotation (m)
ω = object angular velocity (deg/sec).

Due to the change in angular velocity to conserve angular momentum, the object tends to veer, or move radially, in the direction of the Earth's rotation, i.e. to the right in the Northern Hemisphere. Therefore, as water tends to move from an area of high pressure to low pressure, or differences in density, the *CF* causes the flow to move to the right, causing the flow to move along the isobars instead of across them. This geostrophic balance between the horizontal pressure gradient and the *CF* dominates ocean circulation (Stommel 1987).

1.2 GEOSTROPHIC INTENSIFICATION

Geostrophic intensification is the strengthening of the sea surface slope on the western edge of the ocean basins by the combined effects of persistent winds, hydrostatic pressure gradients, the *CF* and restrictive continental landmasses. The rotation of the earth causes objects in motion to curve as the earth rotates away from them, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere as described above. This results in the motion of water along the isobars instead of intuitively across them from high to low pressure. The northern and southern oceanic gyres, in both the Atlantic and Pacific, are essentially a dome of dense, cold water in the center of the respective basins, surrounded by a flowing mass of lighter, warmer water flowing from the equator to the poles along the western edge, and cooler, denser water flowing from the poles to the equator on the eastern side of the gyres. The heating in the tropics and cooling near the poles drives this circulation around the domes. As the water flows towards and along the western boundary, the land mass prevents the water from moving westward, while the rotation of the earth continues to force the water to the west along with the wind-driven flow, thereby piling the water up, creating a larger sea surface slope that results in larger gravitational flows. As the pressure gradient increases, the water attempts to flow to lower pressure but is deflected to the right, i.e. to the north in the Northern Hemisphere, and the flow is driven northwards. The gradient equation defines the relationship between isobar slope (the angle of "piling water") and the *CF* as:

$$\text{Tan}\ \theta = f\ x\ u\ /\ g \qquad (3)$$

where

θ = isobar inclination from horizontal (deg)

f = Coriolis parameter

u = velocity (m/s)

g = gravitational acceleration (9.81 m/s^2).

This equation indicates that if either the isobar slope or velocity changes, at a certain latitude, the other must adjust to maintain equilibrium (Colling 2004).

1.3 CHANNELIZATION

Several locations on the western edges of the ocean basins are arranged such that there is a constriction, or channel, that occurs where the western boundary currents must flow through. The Straits of Florida between Florida and the Bahamas is an example of a constriction through which the Florida Current passes. These locations cause the flow speeds to increase due to the continuity of flow equation:

$$Q = u \text{ x } A \qquad (4)$$

where

Q = volumetric flow rate (m^3/s)

u = water velocity (m/s)

A = cross sectional area of the channel (m^2).

Since the volume of water is constant, the velocity must increase when the area of flow is reduced. While not a significant driving force in the general circulation, channelization can have local effects due more to bottom interaction at the constriction than a substantial change in velocity. This channelization, along with geostrophic intensification and the increase in barotrophic flow resulting from sea surface slope, results in the highest ocean current velocities along the western boundaries of the ocean basins, in both the Northern and Southern Hemisphere. The flows are more intense in the Northern Hemisphere, however, since there are fewer locations with a long length of continental landmass to restrict the flow in the Southern Hemisphere. The major Northern Hemisphere western boundary currents are the Gulf Stream off the eastern United States coast and the Kuroshio Current off Japan, while in the Southern Hemisphere the major currents are the Agulhas Current off southeast Africa, the Brazil Current along the northern coast of South America, and the East Australia Current, or "EAC" from "Finding Nemo" fame. The Antarctic Circumpolar Current is the strongest current system in the world oceans due to a lack of landmass obstructions, and the only ocean current linking all major oceans.

1.4 NORTHERN HEMISPHERE WESTERN BOUNDARY CURRENTS

The Gulf Stream in the northwest Atlantic and its counterpart, the Kuroshio Current in the northwest Pacific, are the two major western boundary currents in the Northern Hemisphere and are important links to the global climate system (Lee et al. 2001). The Northern Hemisphere western boundary currents have stronger relative intensities than the Southern Hemisphere WBCs, and are proximate to major energy consuming populations centers on the eastern seaboard of the United States and the island of Japan, where they hold the potential for ocean energy production. The Kuroshio in the East China Sea is somewhat analogous to the Florida Current in the Straits of Florida, a component of the Gulf Stream, in that both WBCs are separated from ocean basin interior processes by island chains, the Ryukyus and Bahamas, respectively. A detailed comparison of mean flow, however, shows that the Kuroshio is weaker and more surface intensified than the Florida Current, while the Kuroshio transport variability is significantly higher (Lee et al. 2001).

The Gulf Stream originates from waters flowing from the equator into the Caribbean Sea and north through the Mexico straits, entering the Gulf of Mexico as the Loop Current. One part of the equatorial flow diverges, however, and forms the Antilles Current, which flows to the east of the Bahamas and eventually rejoins the Gulf Stream north of the Bahamas (Figure 1). The majority of the flow is channelized through the Loop Current and then between the northern edge of Cuba and the Florida Keys, where it then turns north and flows up the Florida Straits between the Florida peninsula and the Bahamas. This component of the Gulf Stream is known as the Florida Current. In general, the Florida Current is the strongest and most consistent of all the western boundary currents and their components, and will be the primary topic of the rest of this paper.

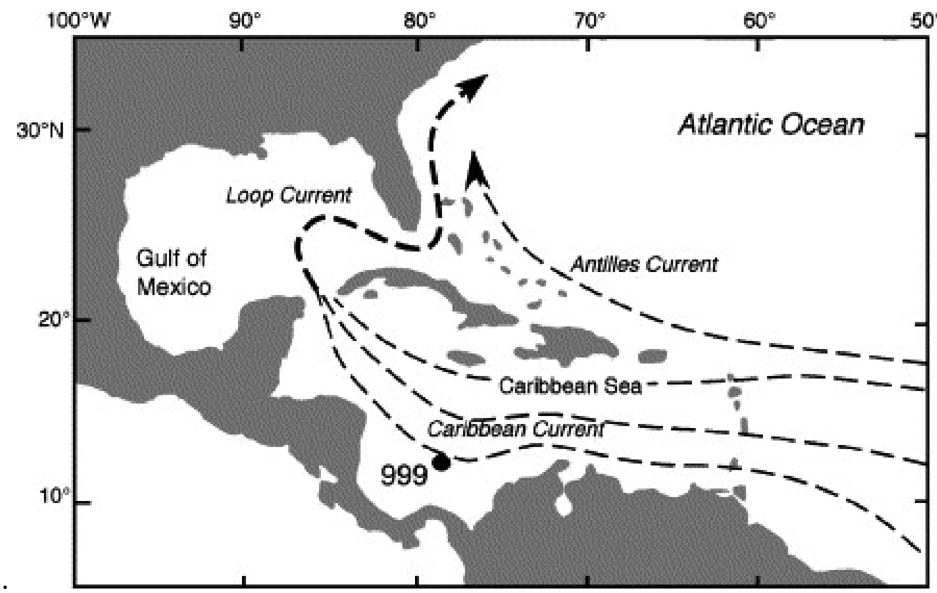

Figure 1. Components of Gulf Stream Origin (Kameo et al. 2004)

2. HISTORICAL MEASUREMENT EFFORTS

2.1 HISTORY OF METHODS

The Gulf Stream has been known for hundreds of years, since Ponce de Leon first described it during his exploration of Florida in 1513. He described a strong northerly flow of water along the east coast of Florida that he could not proceed against, and six years later his pilot, Anton de

Alaminos, used this current for his return to Spain at the end of another expedition. The current became an express route eastward by homebound Spanish ships thereafter (Mills 2009). Benjamin Franklin studied the Gulf Stream off the northeast coast of North America to aid mail delivery across the Atlantic during his time as the first Postmaster General (Franklin 1785). The first comprehensive scientific measurements of the Florida Current portion of the Gulf Stream system were made by the United States Coast and Geodetic Survey between 1867 and 1889. In 1885, 1886, and 1887 Lieutenant J. E. Pillsbury moored the survey vessel Blake directly in the axis of the Florida Current to make direct measurements of the direction and rate of flow using a current meter of his own design (Pillsbury 1891).

During the 20th century, interest in the Gulf Stream and particularly the Florida Current increased as physical oceanographers strove to determine the general circulation characteristics of the North Atlantic Ocean and its probable role in global climatology. The Florida Current, by nature of its close proximity to shore and geographically constrained flow between the Florida peninsula and the Bahamas, was and remains attractive for study due to its logistical accessibility (Leaman et al. 1987).

Efficient direct measurement methods became available and were utilized in the mid 1960's using dropsondes which provided vertical averages of horizontal velocity at various transect locations across the current. These measurements allowed the average flow of the Florida Current to be calculated in much greater resolution than before, and provided the first reliable values for transport, 32 ± 3 x Sv (one Sv, or Sverdrup, is equal to 1 $x10^6 m^3/s$) as the steady state volume transport of the Florida Current (Schmitz and Richardson 1968). Several other studies have been conducted in the Straits to verify this transport value and ascertain whether discernable variability exists, as well as any correlation to the North Atlantic Oscillation.

These measurements have utilized a surprisingly wide range of instruments, from simple drogue chute drifters to complex acoustic Doppler profiler systems, deployed as single units or large arrays, and from combinations of in-water and surface measurement systems. Each approach has advantages as well as specific drawbacks regarding data accuracy and quality. Measurement time duration is important regarding the type and frequency of signals that can be detected.

Section 3 describes the various types of instruments used over the years, their pros and cons, and how well their contemporary data is suitable for use along side recent measurements.

2.2 PRESENCE OF OCEAN CURRENTS

Ocean currents were first noted by sailors who realized their progress was at times slowed and at others increased depending on various locations, both coastally and offshore. The Gulf Stream was discovered by Ponce de Leon on April 22, 1513, and was described in a summary of his log as "A current such that, although they had a great wind, they could not proceed forward, but backward and it seems that they were proceeding well; at the end it was known that the current was more powerful than the wind." (Wilkinson 2000). In addition to the effects on vessel navigation, temperature differences were often noted, in the form of distinct linear fogbanks, the presence of tropical debris in northern latitudes, and marked temperature changes in the holds of sailing vessels during various parts of a voyage. Benjamin Franklin was one of the first to use a thermometer to determine whether a vessel was in a current, in his case the Gulf Stream, as well as a means to locate the flow to benefit a vessel's progress (Franklin 1785). Temperature alone did not provide a magnitude or direction of the flow, so ships were only able to avoid the north-eastern flow of the Gulf Stream on journeys from Europe to North America, and locate and ride the current on the return trip to Europe.

2.3 MAGNITUDE AND DIRECTION

Determining the magnitude and direction of ocean currents, the velocity, was originally obtained from the drift of vessels during voyages across large expanses of water. The largest drifts were noticed during voyages from North America to Europe as a result of the Gulf Stream, and in the Indian Ocean during the monsoonal periods where the local currents occasionally reversed (Mills 2009). Some of the first charts of the Gulf Stream used ship drift as well as noted positions of derelict vessels adrift in the North Atlantic as current indicators (Colling 2004).

As navigation technologies improved, namely due to the invention of the marine chronometer that enabled the accurate determination of longitude at sea, position fixes became more accurate and the resulting current measurements using drift values improved. Sailing ships were still strongly affected by winds, however, so the discrimination of water versus wind influences on drift introduced considerable error into the measurements. It was only towards the end of the 18^{th} century that ocean current measurements began to utilize specialized devices to directly and accurately determine water velocity.

2.4 MEASUREMENT FRAMES OF REFERENCE

The development of mathematics and fluid dynamics directly benefited the field of oceanography from an analytical perspective. In order to develop theories and models, the water motion must be referenced to some unit of measure. Most ocean current measurements are made from instruments installed on moorings or stationary platforms. Such fixed-location measurements are called Eulerian measurements after the Swiss mathematician Leonhard Euler (1707-1783) who first formulated the fixed frame of reference equations for fluid motion. Other means of measuring currents, such as drifters and free floating profilers, measure Lagrangian water motion. The Lagrangian flow description method follows the path of a water parcel over a period of time, and is important in the study not only of water velocity but for determining dispersal rates of substances or biological productivity in the flow volume. This method of describing flow within a moving frame of reference is named after Joseph L. Lagrange (1736-1811), noted for his early work on fluid dynamics and tides (Emery and Thomson 2004). Modern current measurements are often made from moving vessels, where the velocity of the vessel is removed from the water velocity using sophisticated navigation equipment, such as GPS systems or inertial navigation equipment. These moving measurements result in Eulerian values, however, since the positions are georeferenced to specific, fixed locations on the Earth.

3. MEANS OF MEASUREMENT

3.1 THERMOMETERS

The earliest means of directly determining the presence of an ocean current was the thermometer, since most ocean currents flow from distant locations where water temperatures are noticeably different. Benjamin Franklin took water measurements during his trips between Europe and North America, instituted a program of routine temperature measurement, and developed a sailing guide based on water temperature (Franklin 1785). Temperature is required for the accurate determination of density, along with measurements of depth and salinity. Density drives the thermohaline deep circulation which is one of the principle components of ocean circulation, the other being wind-driven surface currents (Stommel 1965).

A high level of accuracy is required for water temperature measurements because of the relatively large effects that temperature has upon the density and other physical properties and because of the extremely small variations in temperature found at great depths. Subsurface temperatures must be accurate to within less 0.05 °C, and under certain circumstances to within 0.01 °C for the calculation of geostrophic velocity and deep ocean density structures (Sverdrup 1970).

The core of the Gulf Stream was defined for more than 100 years as the location of maximum temperature, and numerous charts and theories were based upon this characterization. In 1883 Lieutenant, J. C. Fremont, Jr., U. S. N., conducted the first investigation of the Gulf Stream from a vessel at anchor. Using a sort of drifter device consisting of cans attached to a log line, he discovered that the greatest velocity was not found at the supposed center of the stream as determined by maximum temperature, but “somewhat to the west of it.” (Pillsbury 1891). This discovery forced scientists to rethink how to determine the maximum flow axis as well as the mechanisms which causes the phenomenon.

3.1.1 TYPES OF THERMOMETERS

Historical water temperature measurements usually employed a glass thermometer attached to some sort of weight to allow the device to sink to a desired depth, or simply to keep it vertical alongside a moving vessel. The measurements, while of value to navigation, were not sufficient to accurately measure temperature at depth for various reasons. The types of thermometers used in physical oceanography are the analog type, which directly indicates a physical change, and the electronic type that converts a physical property into an electrical voltage or digital signal.

3.1.1.1 ANALOG THERMOMETER

The analog thermometer is based upon the expansion of a liquid, namely mercury for oceanographic use, which changes volume linearly with changes in temperature. Issues that may affect this sort of thermometer are the glass bulb's lack of resistance to high pressures during deep-water measurements and the change in measured temperature at depth as the active thermometer is brought through the oceanic vertical temperature gradient to the surface. This sufficiently alters the readings such that it is not possible to accurately measure the deeper temperatures with a direct reading thermometer (Emery and Thomson 2004). The solution requires a sufficiently strong device that obtains the temperature measurement at depth, and does not change upon return to the surface. This type of analog thermometer is known as a reversing-thermometer. This device measures temperature at depth and just before retrieval the thermometer rotates 180 degrees, or "reverses". The design of the mercury tube causes the column of mercury to break, thereby locking the measurement value in place so that it does not change upon return to the surface (Sverdrup 1970).

The accuracy of a reversing thermometer is based upon the precision at which this break occurs, and in a high quality device this precision is better than 0.01°C. Emery and Thomson (2004) stated other issues which may affect temperature measurement precision are:

a) Linearity in the expansion coefficient of the liquid
b) The uniformity of the capillary bore
c) The constancy of the bulb volume
d) The exposure of the thermometer stem to temperatures other than the bulb temperature.

Mercury exhibits a well-known linear response to changes in temperature, and with modern manufacturing techniques, capillary bore uniformity is no longer a major concern. Repeated exposure to high pressure may produce permanent deformation and a subsequent change in bulb volume, and improper mounting may insulate the stem or bulb such that there is a temperature difference between the two parts of the device. Exposure to temperatures above the design range of the device (such as those experienced on a hot deck in the tropics) may also increase the frequency of required calibrations. Operational calibration aboard ship may be conducted thru the determination of the "ice point" (a slurry of ice and water), while annual calibrations should be conducted in a laboratory using the above method, as well as comparison with calibrated reference thermometers.

There are two basic types of reversing thermometers, 1) protected thermometers which are completely enclosed in a pressure resistant housing and do not experience hydrostatic pressure, and 2) unprotected thermometers for which the glass jacket is open at one end so that the bulb is exposed to pressure, resulting in an apparent increase in the measured temperature. The apparent increase is due to the compression of the glass, which changes the bulb volume, so corrections from the manufacturer, or those obtained by calibration under pressure, must be applied to measurements made with an unprotected reversing type thermometer. A useful feature of this variability is the determination of measurement depth by comparing the temperature from an unprotected thermometer with a protected thermometer, and can result in depth accuracies of within 1% of actual depth (Emery and Thomson 2004). The difference represents the hydrostatic pressure at the depth of reversal. The reversal depth is calculated from the expression:

$$D = T_{\mathrm{u}} - T_{\mathrm{w}} / Q_p \rho_{\mathrm{m}} \qquad (5)$$

where

D = reversal depth (m)

T_{u} = reading of the unprotected thermometer (°C)

T_{w} = reading of the protected thermometer (°C)

Q_p = pressure constant

ρ_m = mean density *in situ* of the overlaying water (kg/m^3).

Q_p is based upon the specific thermometer of interest in degrees increase in apparent temperature due to a pressure increase of 0.1 kg/cm^2 (Sverdrup 1970).

The few disadvantages of analog thermometers are that they cannot be read in real-time, they must be recovered to read, and they cannot measure a complete temperature versus depth profile using a single device during one deployment. Glass thermometers are susceptible to shock and rough handling, which can be especially important during deployment and recovery in rough seas, where the sampling device may impact the ship or deck and damage the devices. The reliability and calibrated accuracy of analog thermometers, however, continue to provide a standard temperature measurement against which all forms of electronic sensors are compared and evaluated, and are a standard component of modern deployments for this purpose.

3.1.1.2 ELECTRONIC THERMOMETERS

Electronic thermometers are the most common type used in oceanography today, due to the real-time measurement capability and ease of integration into automatic data collection systems. Since the electrical resistance of metals, and other materials such as semiconductors, changes with temperature, these materials may be used as temperature sensors.

3.1.1.2.1 METAL-BASED SENSORS

For most applications the change in a metal's resistance is assumed constant, and the proportionality of this change is given by the temperature coefficient α. Copper, platinum, and nickel are the most commonly used, with α values of 0.0043, 0.0039, and 0.0066 $(°C)^{-1}$, respectively (Emerson and Thomson 2004). Note the values of α are positive, indicating resistance increases with increasing temperature. Of these metals, platinum is the metal of choice since copper has such a low electrical resistance a thermal element would require many turns of fine wire, which would be expensive, while nickel has a high electrical resistance but deviates sharply from linearity. The platinum resistance thermometer, or PRT, is the most common electronic temperature measurement device in use in CTD systems, weather stations, and other non-expendable measurement systems. Modern PRT sensors have accuracies of +/- 0.002 °C over a range of -3 to 32 °C and a stability of 0.001°C /month, while a laboratory calibration standard PRT can have accuracies of +/- 0.001 °C (Emerson and Thomson 2004).

3.1.1.2.2 Semiconductor based devices

Semiconductors also exhibit resistance change with changing temperature, in some cases up to 10 times the response speed of metals with α = -0.05 $(°C)^{-1}$, but their resistance is inversely proportional to increasing temperature, i.e. their resistance decreases with increasing temperature. These devices, usually mixtures of metal oxides such as nickel, manganese, and cobalt, are commonly known in oceanography as thermal resistors, or thermistors. The temperature response, unlike metals, is nonlinear, but may still be used to determine temperature by the equation:

$$R(T) = R_0 \exp[\beta\,(T^{-1} - T_0^{-1})] \qquad (6)$$

where

β = material constant specific to the type of device

T = absolute temperature with the respective resistance values of $R(T)$ (°K)

T_0 = absolute temperature with the resistance value of R_0 (°K)

R_0 = conventional temperature coefficient of resistance β / T^2.

This relationship allows for the determination of temperature T from the measured resistance $R(T)$ (Emerson and Thomson 2004).

3.1.2 THE CTD UNIT

A CTD unit measures Conductivity, Temperature, and Depth at very specific depths with highly calibrated sensors. The conductivity sensor measures the electrical conductivity of the water, related to the amount of chlorine ions in solution, which along with temperature and depth allows calculation of salinity, providing precise water density profiles. The CTD is lowered from a surface vessel by an electrical cable (Figure 2), allowing for real time data collection, and is deployed with a rosette of sampling bottles. These bottles are triggered to close at specific depths, obtaining samples for additional laboratory analysis to compare with the CTD or identify other water properties. Reversing thermometers provide a means of validating depth and temperature measurements.

Figure 2. CTD Rosette System (CTD below sample bottles on frame) (Photo by author)

3.1.3 EXPENDABLE BATHYTHERMOGRAPH (XBT)

Since thermistors are semiconductor based, usually mass-produced at very low unit cost, and exhibit fast response times, they are used primarily in expendable measurement devices, such as the expendable bathythermograph, or XBT. These devices are typically deployed over the side of a vessel and free fall to the seafloor, continuously recording temperature readings thru the water column. The XBT probe consists of a molded projectile with a thermistor recessed in the nose which falls through the water column at a relatively constant free fall velocity. The sensor housing, as well as the launcher tube, contains a roll of fine copper wire, which pays out from both ends with zero tension, so that the probe is isolated from the motion of the vessel. The resistance of the thermistor is sensed through the copper-wire link to the surface recording device continuously in real time. Depth is determined from a rate of fall equation and temperature from a resistance-temperature relationship (Georgi et al. 1980). When the probe reaches the seafloor or the extent of its wire payload, the wire is broken and the probe remains unrecovered on the bottom. While a convenient and relatively inexpensive means of measuring a temperature profile, the main sources of error with the XBT are the consistency of the thermistors from one unit to the next and the actual free-fall velocity versus the manufacturer's stated value.

Unlike a temperature measurement device that is used repeatedly and is available for calibration, XBTs are single use, sealed units that are not readily tested prior to deployment. The manufacturer provides information regarding temperature conversion and sensor accuracy. The primary XBT manufacturer, Lockheed Martin Sippican Inc., states the accuracy of the system is +/- 0.1 °C . A study of 18 cases of probes (12 probes per case) were made comparing the temperature readings with that of a calibration water bath, and resulted in a standard deviation for the probes of 0.023 °C which was reduced to 0.021 °C when considering the inherent variability of the testing procedure. The report also stated that, due to the similarity of XBT thermistors and the difficulties encountered attempting to do temperature calibrations to 0.001 °C accuracy, individual probe calibration is probably not warranted (Georgi et al. 1980).

Besides temperature variations, apparent systematic differences between isotherm depths obtained by XBT and CTD in the same area have been noted. In all cases the XBT temperatures were systematically higher than CTD temperatures at equivalent depth (Heinmiller et al. 1983). The results indicated the mean value of depth differences between XBT and CTD measurements was approximately 10 m, and was independent of location during the profile. This implies the calculated fall rate of the XBT may not accurately determine measurement depth, where the use of a pressure sensor in the CTD does so by direct measurement. In comparison with the average temperature disagreement of 0.17 °C, however, this depth disparity was insignificant and unnecessary to include in correction calculations. Another comparison was made in 2000 and determined that, on average, XBT temperatures were 0.1°C to 0.4 °C higher than CTD measurements at all levels (Schmeiser 2000).

In practice, XBTs are used alongside CTD casts, and are used to fill in between CTD stations where their temperature and depth accuracy is acceptable. The ease of deployment, and the ability to deploy while the support vessel is underway can provide additional temperature profiles much faster and efficiently, and supplement the more rigorous CTD measurements in a region of study. They are also useful for rapid sound speed profile measurements (Leaman and Vertes 1995).

3.2 CURRENT MEASUREMENT DEVICES

3.2.1 SURFACE DRIFTERS

The oldest type of current measuring device is a surface drifter, originally sailing vessels whose course was altered by water flow during their voyage or the wanderings of derelict ships (Sverdrup 1970). This method of measurement is still in use, and has transitioned into the use of specifically designed drifting instruments. Drifters act as Lagrangian tracers embedded in the moving fluid, and when properly designed move with the currents and are little affected by the wind (Strangeways 2000).

The first focused use of drifters as a means of determining current patterns was initiated by the Prince of Monaco in 1885, where he deployed "no less than one thousand six hundred and seventy five of these floats" from his royal yacht throughout the south-eastern region of the North Atlantic, primarily to discover the departure of sardines from the Bay of Biscay. The floats, consisting of barrels, bottles, and specially constructed copper globes, were individually marked and ballasted to minimize the effects of the wind. Their eventual recovery positions and times provided a substantial amount of information during the late 1800s concerning the eastern portion of the Gulf Stream (Pillsbury 1891).

Modern surface drifters no longer rely on discovery and reporting from ships of opportunity for their measurements. They instead utilize various electronic means of location determination, and present systems use satellite-based Global Positioning System (GPS) receivers for accurate tracking (Anderson and Sharma 2008). Prior to GPS, however, drifters were tracked with a variety of radio-based systems. A drogue study in the Straits of Florida was conducted in 1967 and utilized a Decca Hi-Fix navigation system, along with strobe lights for visual tracking at night. The drogues were tracked for 27 hours and provided valuable insight into the behavior of the very shallow portions of the Florida Current (Chew and Berberian 1970).

The drogues were of conventional design, consisting of a small surface float suspending an 8.53 m diameter parachute lowered to a nominal depth of 47 m below the sea surface. They were set adrift and followed with a vessel, which would come alongside the drifter at intervals, estimate a distance to the drifter, and then obtain the location of the vessel from the Decca Hi-Fix system.

The Decca Hi-Fix system used the ranges to two shore based radio towers at known locations to triangulate an offshore position, although accuracy was dependent upon line of sight distance between towers and vessel, baseline distance between towers, and atmospheric propagation effects. The procedure for reducing Hi-Fix readings to x,y distances also provided error estimates based upon these factors, and for this study the errors amounted to 170 m within the last three hours of the test. The distance between the ship and drogue also introduced error and was estimated at about +/- 50 m. For most of the experiment, however, errors were estimated between 15 to 30 m for Hi-Fix, plus the +/- 50 m from ship observational errors (Chew and Berberian 1970).

Despite these positioning issues, the general behavior of the Florida Current at scales of 1 km and larger were detected. Throughout the next two decades other shore-based systems, such as Loran-C, offered improvements, but the need for higher-resolution positioning remained. This issue was finally solved with the implementation of GPS technology in the 1990s and improvements in resolution to less than 6 m on May 2, 2000 when the selective availability feature (used to degrade GPS accuracy) was permanently deactivated (NOAA Website 2012).

Present-day drifters are routinely deployed in the Gulf of Mexico for tracking Loop Current eddies. These large scale eddies, which separate from the Gulf Stream portion entering the lower Gulf of Mexico, can potentially affect oil production operations and are therefore actively monitored. Over 2200 satellite-tracked drifters have been air deployed into the Gulf of Mexico since 1985 to monitor the Loop Current (Anderson and Sharma 2008). The drifters are highly sophisticated devices, with satellite tracking and telemetry, and advanced drogue anchors that hang suspended under the float several meters below the surface to reduce wind drift effects. Once the drifters complete a circuit of the Gulf, they often become entrained in the Florida Current and drift past the Keys and through the Florida Straits.

Drifter use in high velocity currents like the Florida Current have been restricted due to the very high velocities of interest, in that the instruments are swept through the area before much data is collected. For short timescales, however, they are useful for targeted studies of specific flow features in the current.

3.2.2 DROPSONDES

A technique was developed in the mid-1960s to determine vertical averages of horizontal velocity at a point in a current (Schmitz and Richardson 1968). A device known as a dropsonde was developed that recorded temperature and pressure and was equipped with a release mechanism to release a drop weight upon contact with the seafloor (Figure 3).

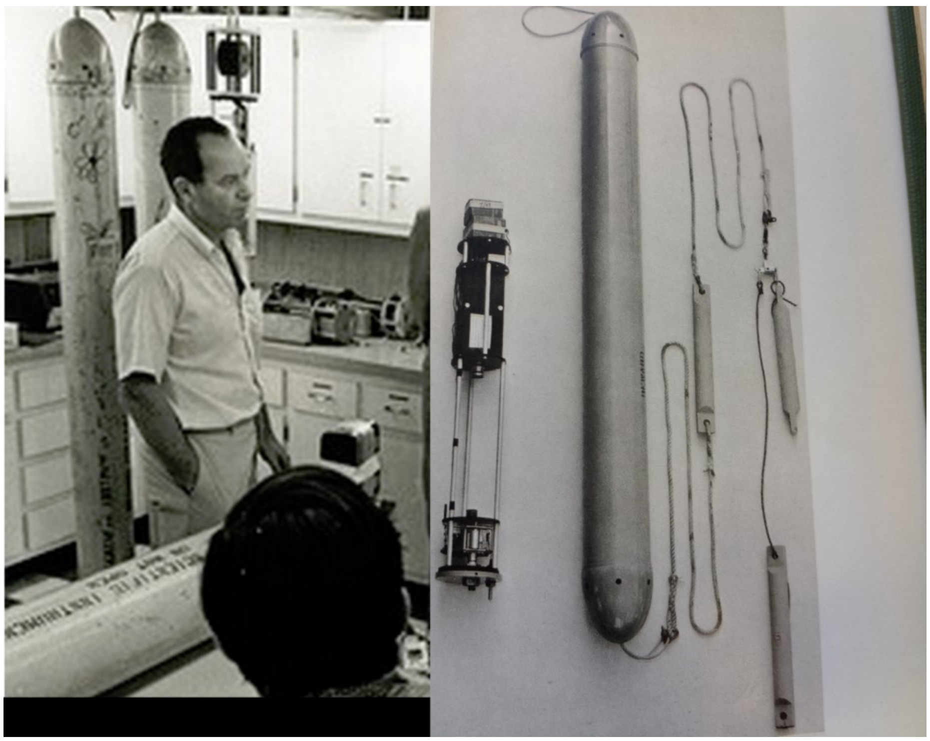

Figure 3. Dropsonde (right), and Richardson in lab with units (Photo from P. Spain)

The unit would be dropped at a specific location, it would fall to the seafloor, release its weight, and then float back to the surface for recovery. Based upon the horizontal translation of the device during its fall and ascent through the moving current, the vertical-mean horizontal velocity could be calculated. The pressure and temperature sensors provided insight into the vertical structure of the current, indicating the location of the thermocline and other features. The first accurate transport values of the Florida Current were obtained using this device in the late 1960's (Schmitz and Richardson 1968). The difficulty in locating the device upon surfacing led to the development of more accurately tracked dropsonde units, namely the Pegasus profiler.

3.2.2.1 PEGASUS

In its simplest form, the Pegasus was an acoustically tracked dropsonde which fell or rose at a rate of 20-70 cm/s depending on the instrument configuration and emitted a 10-khz acoustic tracking ping at a predetermined rate. The profiler listened for response pings at two or more of a set of four frequencies: 13.0, 12.5, 12.0, and 11.5 kHz (Leaman and Vertes 1995). Response pings were generated by acoustic transponders, previously deployed in an accurately known configuration on the ocean floor and programmed to listen for and reply to the 10 kHz interrogation pulse. Although three transponders provided enough information to locate a Pegasus in 3-dimensional space, it was more common to use two transponders and rely on pressure to provide the third coordinate (Wilburn et al. 1988). By actively tracking the probe during descent and ascent (Figure 4), a full water column estimate of absolute horizontal velocities was obtained (Meinen et al. 2010).

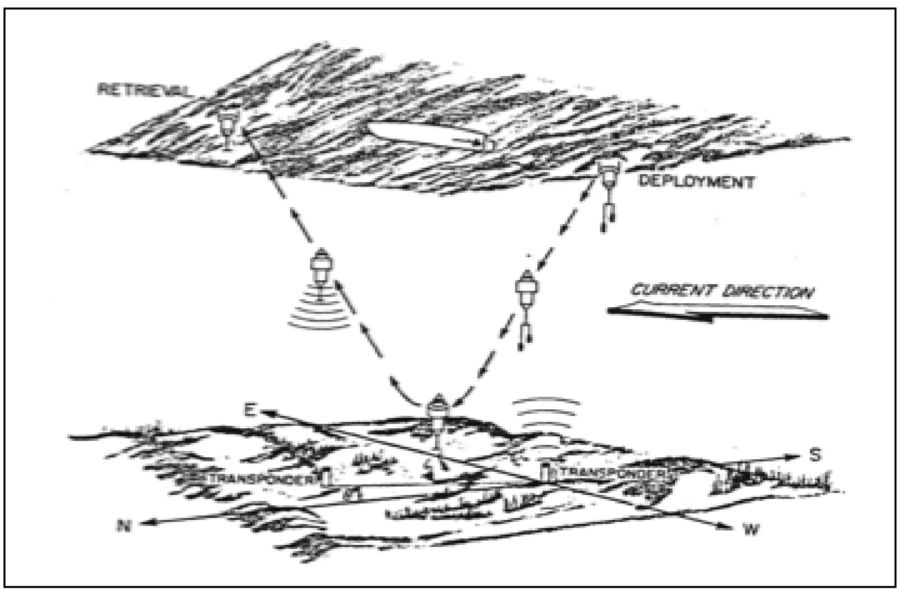

Figure 4. Pegasus Measurement Profile Diagram (Wilburn et al. 1988)

Velocity profile accuracy depended on how well the depth of the two transponders, the length and orientation of the baseline that connects them, and to some extent whether the sound speed profile was known prior to deployment. It was found that knowledge of the temperature profile from a XBT or the profiler itself, plus a temperature-salinity curve was adequate to obtain a sufficiently accurate sound speed profile. A survey vessel determined the bottom position of the transponders prior to deployment. Any errors in determining these locations would produce systematic (rather than random) errors in the resulting velocity profiles, as would calibration errors in pressure if used for the third coordinate. Other 'drop dependent' errors depended on the physical location of the profiler relative to the transponder grid. For example, errors were amplified if the profiler drifted too close to the baseline.

Choice of ping repetition interval (8 or 16 s) depended mainly on water depth. Sufficient time was required for multiple echos to clear out before the next tracking ping was sent, since location was based upon a 'first return' signal detected by the probe. Given the effort and cost required to deploy a Pegasus station, the system was most suited to situations in which 1) a station could be visited numerous times during the lifetime of the transponders; 2) enough was known about the currents in the area so that a reasonable choice of station locations could be made; and 3) with limited ship time, a reasonably small number of stations was sufficient for the work (Leaman and Vertes 1995).

3.2.2.2 POLARIS

Polaris was an upgraded prototype version of the Pegasus that used GPS navigation and surface-floating transponders instead of the bottom mounted units as with Pegasus. The objective was to eliminate the need to survey in the bottom transponders with the support vessel. The positions of these hydrophones were computed every few seconds using GPS, while other features of deployment and measurements were similar. The main drawback of the Polaris system was that in the strong Florida Current the devices were advected northward at such a rapid rate their residence time in the area of study was short and they had to be recovered and redeployed more often than the bottom transponders of the earlier Pegasus system (Leaman and Vertes 1995).

The cost of maintaining the acoustic baseline for Pegasus systems in the Florida Current became too costly in the late 1980's, so the units were used as basic, non-tracked dropsondes which yielded only vertical mean horizontal velocity similar to the earlier dropsondes. In 1994 a newer generation dropsonde was developed with an internal recording GPS receiver, which is still in use (Meinen et al. 2010).

3.2.3 CURRENT METERS

The oldest and most common type of instrument used for measuring Eularian current magnitude and direction is aptly known as a current meter. The basic function of a current meter is to resolve the water velocity reliably and consistently for a sufficient period of time to resolve the desired flow characteristics. Two general classes of current sensor have been used, the mechanical (moving parts) and electronic (no moving parts). Mechanical sensors include moving rotors, propellers, and impellors for velocity, and vanes for determining direction. Electronic sensors include electromagnetic, acoustic travel time, and acoustic Doppler sensors which detect changes in transmitted acoustics to determine velocity (Dean 1985).

3.2.3.1 MECHANICAL CURRENT METERS

Mechanical current meters determine flow speed by the movement of a rotor caused by the water flow, while direction is determined either by a vane fixed to the meter to orient it into the flow or separate but collocated vanes which only determine flow direction. All directions are relative to the meter axis and referenced to magnetic north using an integrated compass.

3.2.3.1.1 PILLSBURY CURRENT METER

The first current meter used to specifically measure the velocity of the Florida Current was a prime example of mechanical ingenuity well before the sophisticated electronics of the late 20th century. Many of the same principles are still used in contemporary current measurement equipment and techniques. Pillsbury (1891) summarized the essence of current measurement in the following statement:

> In order to obtain the velocity and direction of the current at any depth it is necessary to have a registering apparatus recording the flow of the water, a rudder which is free to assume a position in the direction of the flow, a compass to show the azimuth of the

rudder, and a system by which these may be stopped at any desired time and held fast until the instrument can be hoisted to the surface and the data read. (525)

He described, with the exception of the need to bring the device to the surface to make a reading, the fundamental requirements of oceanographic current measurements. He achieved these requirements with a remarkable device of his own design, without the use of any other equipment except for a timepiece, cable winch, and courageous crew.

The Pillsbury current meter (Figure 5), built in 1885, consisted of an elliptical framework with a locking mechanism attached to a ring that surrounded the "velocity apparatus" and rudder vane (Pillsbury 1891). Two horizontal vanes, or fins, were attached to the locking mechanism. The apparatus was very similar to the modern day cup-anemometer design, where four hollow cones were mounted on spokes, such that while one open end of a cup faced into the flow, the opposite cup would present it's pointed end to the flow. The rotor axis turned a worm gear, which drove geared wheels to count revolutions on a dial indicator. The rudder tended to align itself with the flow, and was connected to a compass needle in a weighted, gimbaled bowl. Various linkages connected the rotor counter and compass needle, and those linkages were in turn attached to the fins on the main locking ring mechanism. After the desired sampling interval, the meter was hauled upward thru the water, and the drag of the water on the locking fins engaged the locking mechanism, securing both the rotor count and compass direction at that instant (Pillsbury 1891).

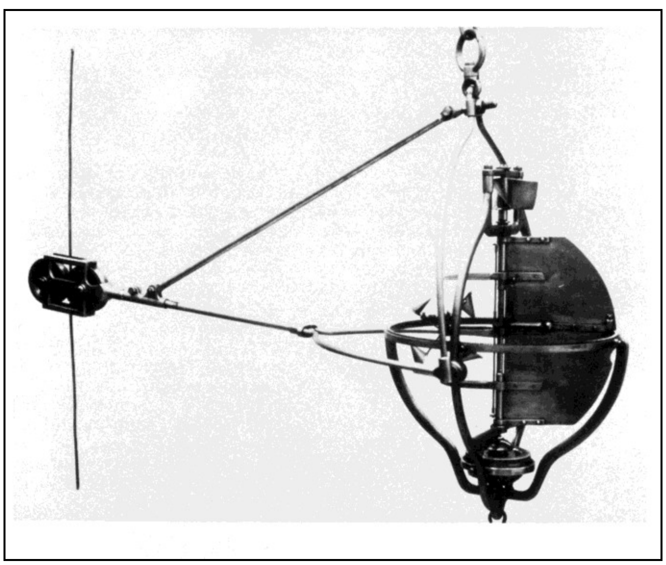

Figure 5. Pillsbury Mechanical Current Meter 1885 (Pillsbury 1891)

Pillsbury (1891) described the procedure as such:

> The action then is: the meter is lowered to any desired depth and a certain time allowed for it to register the velocity of the current. At the given signal it is hoisted, and immediately upon starting to rise through the water the pressure upon the fins secures the rudder and the compass needle. (526)

He further emphasizes from an operational perspective, “as long as there is a continuous motion in the same direction both will remain secured until the surface of the water is reached.” (Pillsbury 1891). If not, then the lack of force on the locking fins would release the lock and allow the rotor and vane to adjust to the surrounding flow, resulting in erroneous readings. Assuming a successful recovery, a crewman would read the meter and compass, pass the readings to the data collector, reset the device, and lower it to the next depth of interest. A photo of the deployment apparatus and the fearless crewman (standing under winch sheaves) who read the instrument are shown below (Figure 6).

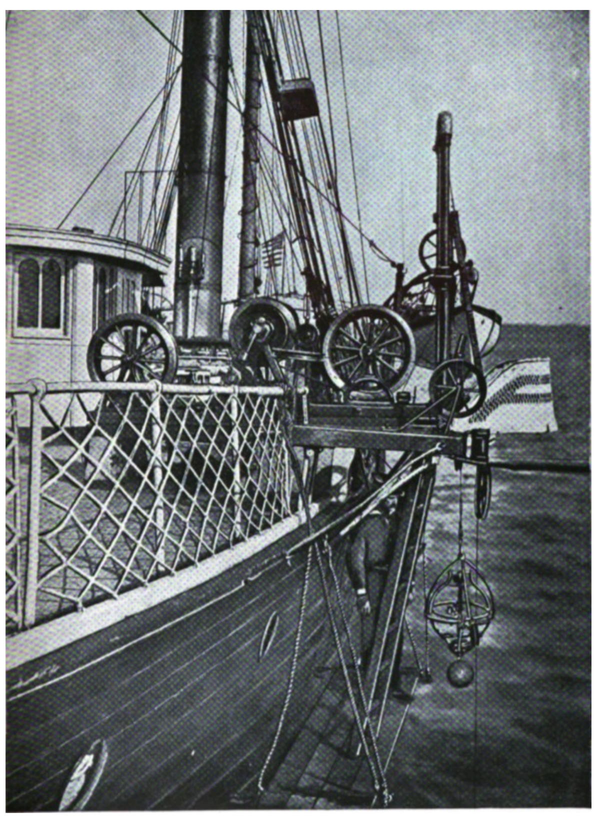

Figure 6. Deployment of Pillsbury Mechanical Current Meter (Pillsbury 1891)

This procedure enabled Pillsbury to obtain accurate velocity measurements at any depth desired, although he was primarily interested in the flow at depths between 3.5 and 130 fathoms (6.4 and 237.7 meters).[1]

3.2.3.1.2 RECORDING CURRENT METER

The development of reliable, self-recording current meters was one of the major technological advancements in oceanography. The age of the modern current meter began with the development of the Aanderaa Recording Current Meter (RCM) in Norway in the early 1960s under the sponsorship of the North Atlantic Treaty Organization (NATO) (Emery and Thomson 2004). The RCM is a non-averaging current meter that uses a Savonious rotor to measure current speed and a vane to determine current direction. The Savonious rotor consists of six axisymmetric, curved blades enclosed in a vertical housing that is oriented normally to the direction of flow, and provides an omnidirectional response to water motion. The directional vane is connected directly to the body of the meter, and pivots about the mooring attachment in response to water flow. The RCM electronically counts the number of rotor shaft rotations versus time to determine flow magnitude, and instantaneous flow direction is determined from the vane and internal compass. Thus the speed is determined by total number of rotor revolutions over the time interval while the direction is determined at the end of the sampling period. While the RCM does not calculate velocity vectors internally, they may be computed during post-processing. Velocity values are converted into physical units using calibration constants for each device, obtained thru laboratory testing prior to deployment. For most constants, they are obtained by a simple quadratic fit to calibration data, while direction is found by a compass-specific lookup table (Emery and Thomson 2004).

Three major drawbacks to the RCM type current meter are 1) lack of on-board burst sampling and averaging, which saves storage space and increases the deployment duration capability by

[1] For historical purposes, Pillsbury depth measurements are presented in fathoms, which are equivalent to 1.8288 meter per fathom, and units of transport in long tons of water (35 ft^3 of sea water with a density of 64 pounds/ft^3), or approximately one metric ton. Metric equivalents are provided in parenthesis.

sampling very rapidly for a short period of time; 2) the direction measurement only at the end of the sampling period; and 3) issues with the Savonious-type rotor. In complex current flows where direction and magnitude change at various temporal scales, the RCM is capable of only determining the average flow and direction at the end of the sampling interval. The direct mounting of the vane to the meter also retards proper alignment in low flow, although in high currents this is rarely a problem except for additional hydrodynamic drag from the large vane. (Figure 7) shows the meter with the large directional vane and mooring pivot attachment.

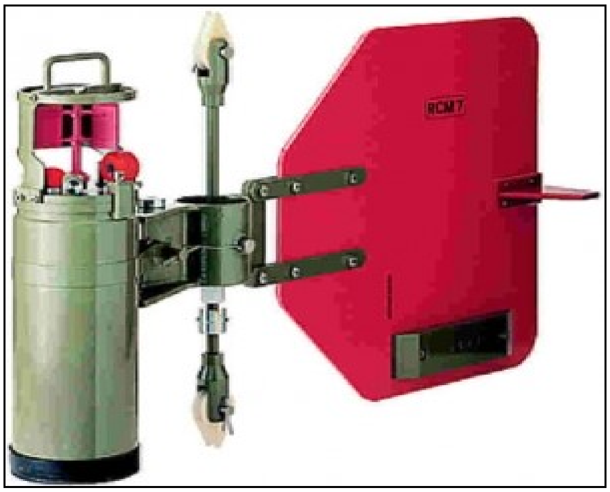

Figure 7. RCM with Savonius rotor and large directional vane (Aanderaa Instruments)

The Savonious rotor has an omnidirectional response, which is preferable for a single rotor current meter in steady horizontal flow. This characteristic, however, makes the rotor highly susceptible to errors caused by oscillatory motions, such as those caused by surface waves and motions from surface-following buoys. The vertical velocities are included in the rotor motion and recorded. This effect is know as wave pumping, and significantly increases the spectral energy at both low and high frequencies. For this reason, current meters using the Savonius rotor are best deployed on subsurface moorings well below the influence of surface waves (Woodward et al. 1990).

Another issue with Savonious rotors, as well as most other mechanical meters, is that bearing friction results in fairly high threshold speeds, that is the velocity required to start the rotor turning. This value, depending on level of maintenance and length of deployment, may be as high as 2 cm/s, and in low flow regions may result in periods of no data. Once rotating the response is fairly linear from 2.5 to about 250 cm/s with an accuracy of +/- 1 cm/s or 2% maximum speed, whichever is greater (Emery and Thomson 2004).

3.2.3.1.3 VECTOR AVERAGING CURRENT METER

Vector averaging current meters (VACM) also utilize a Savonius rotor, and exhibit the same limitations for that type rotor as the RCM, but incorporate a separate directional vane, which exhibits better response than the large vane on the RCM in low flow. The meter electronics utilize burst sampling and converts the velocity into vector quantities, north (v) and east (u) components of the flow. The vector averaging saves data storage, allowing for longer deployments, and reduces post-processing efforts. Burst sampling tends to eliminate a large proportion of surface-wave-frequency contamination in areas of high wave conditions and near-surface installations (Woodward et al. 1990).

3.2.3.1.4 VECTOR MEASURING CURRENT METER

The Vector Measuring Current Meter (VMCM) is a further improvement on the VACM, and was essentially the last mechanical current sensor introduced to ocean measurements (Williams 2010). The VMCM carries two orthogonal propeller-type rotors (Figure 8) designed for good cosine response.

Figure 8. VMCM (note two white orthogonal rotors) (Photo by D. Blackwood WHOI)

This term refers to the dependency of the measured flow on the angle of attack of the incident current. This implies that the flow parallel to the axis of the sensor is unity and properly measured, while the response would be zero for flows normal to the axis, thereby allowing the meter to operate properly even in regions of vertical motion (Dean 1985). The rotor outputs are transformed into *v* and *u* components onboard and only vector averages are recorded, similar to the VACM device.

3.2.3.1.5 NISKIN WING CURRENT METER

While not exactly a mechanical current meter, the Niskin wing current meter was widely used alongside mechanical meters and employed a novel means of determining flow and direction. The winged housing would be installed with a clamp-on mooring standoff device (Figure 9) such that when deployed it would be turned in the direction of the flow and swept away from vertical by the water current. The amount of the housing tilt provided speed and direction of the current, which was determined by an internal force-balance tilt sensor and three-axis flux gate magnetic compass. Other sensors included temperature, conductivity, and pressure (depth).

Figure 9. Niskin Wing Current Meter installed on mooring wire (University of Miami)

The meter advantages were the absence of external moving parts that could be clogged, fouled, or dislodged, its accuracy was not affected by tilt and/or motion of the mooring line, and it utilized both burst sampling and internal vector averaging. Drawbacks included difficulty calibrating without specific test fixtures and a stable, non-moving location (not aboard ship), and they would not "fly" properly if the tether was fouled during deployment.

3.2.3.2 NON-MECHANICAL CURRENT METERS

While mechanical current meters effectively determine current magnitude and direction thru the direct action of the flow itself, they only provide a point measurement of the overall water flow. Multiple meters must be deployed to cover even a modest area, and certain assumptions must be made about the flow not measured during the experiment. Several other means to measure water flow have been developed that can determine flow over a large area, even the entire width of the Florida Straits. These include induced electromagnetic signals, acoustic methods, and surface-current measuring radar systems.

3.2.3.2.1 ELECTROMAGNETIC

Electromagnetic current meters take advantage of the fact that flowing seawater is a moving electrical conductor, and based upon Faraday's law of electromagnetic induction, induces a voltage proportional to its velocity as it passes thru a magnetic field. Depending on whether the magnetic field is the Earth's or a field generated by the sensor itself, large-scale current measurements or point measurements may be made from flowing water.

Large scale ocean current measurements are possible using submarine communication cables equipped with the appropriate instrumentation using this phenomenon (Baringer and Larsen 2001). When seawater passes through a stationary magnetic field (the Earth's magnetic field), the induced voltage is proportional to the vertically averaged water velocity within a horizontal radius of a few water depths (Chave and Luther 1990). The measurement of the resulting horizontal electric field (HEF) yields direct observations of the barotropic transport in the overlying water column, and for a submarine cable, the motional HEF is integrated along the cable length. Measurement of the HEF is entirely passive, nonintrusive, and uses very low power (Emery and Thomson 2004). This method has been used for decades to monitor the Florida Current transport between Florida and the Bahamas.

Point measurements may be obtained using much smaller instruments than subsea cables, the main difference is the meter generates a localized magnetic field instead of using the much weaker, but ubiquitous, planetary magnetic field. In essence, using a local magnetic field with knowledge of orientation, both magnitude and direction may be determined from the current.

A two-axis electromagnetic current meter with an internal compass may be used to produce horizontal components referenced to earth coordinates (North and East typically). The induced voltage potential E in volts is found by Faraday's Law through the cross-product:

$$E = \int_{L}^{\infty} v \times B \, dL \qquad (7)$$

where

v = flow velocity past the electrodes (m/s)

B = instrument applied magnetic field (T)

L = distance to the coil center (m).

The magnetic field is directed vertically past the electrodes so that current flow parallel to the x-axis generates a voltage along the y-axis that is proportional to the strength of the current, and is determined for the y-axis in a similar fashion (Emery and Thomson 2004).

Sensors may be configured in small (5 to 10 cm diameter) spheres for compact units, as well larger 25 cm spheres for wave and mean current measurements (Figure 10).

Figure 10. Marsh McBirney 2-inch EM current meter (photo by author)

The sensors perform well in oscillatory motion, such as near the surface or attached to surface platforms, and their streamlined shape (spherical) and lack of mechanical components improve their deployment reliability. Laboratory studies suggest that spherical electromagnetic sensors may be sensitive to free stream turbulence and wakes behind the probes, as well as boundary layer separation in certain flow conditions (Guza et al. 1988). Deployments in locations where these conditions may exist require housings with features to maintain the boundary layer, or use other means to prevent wakes and turbulence.

3.2.4.2 ACOUSTIC SENSORS

The most recent, and most widely used, method of measuring water velocity is the acoustic current meter, ACM. ACMs play a major role in modern current measurements. They have no external moving parts and make their measurements some distance away from the structural support of the acoustic transducers and thus may be considered minimally invasive, measuring an undisturbed flow (Williams 2010).

3.2.4.2.1 POINT MEASUREMENT ACM

The basic ACM measures the difference in the time delay of short, high frequency (megahertz) sound pulses transmitted between an acoustic source and receiver separated by a fixed distance at a specific location in the flow (Figure 11).

Figure 11. Acoustic Current Meter point measurement device (Gilboy et al. 1999)

The greater the current speed in the direction of sound transmission, the shorter the time delay between the transmitter and receiver. Likewise, the sound pulse in the direction opposing the flow takes longer to reach the receiver. The arrangement of transmitter and receiver pairs, typically on two or three orthogonal axes, allows the determination of water velocity.

Speed accuracies of +/- 1 cm/s may be obtained at flow speeds of 10 cm/s, with a resolution of approximately +/- 1 mm/s. The speed range typically measured by commercially available ACMs is zero to 5 m/s, and operate at acoustic frequencies of 4 MHz sampling at 20 Hz or higher. Due to the short baseline between transmitter and receiver, ACMs are less susceptible to instrument tilt than other types of sensors, particularly mechanical meters.

ACMs are highly sophisticated instruments and susceptible to damage and physical effects that may alter their calibration. Problems with sensor alignment and changes in the physical dimensions of the transmit/receive pairs due to mechanical and environmental affects have been documented. ACMs also require a zero level definition since there is no inherent “zero flow” signal that corresponds to a physical flow. Issues with amplifier gain and electronic noise must be quantified and removed from the data collection system prior to deployment, and are subject to occasional drift during operations. Recent manufacturer improvements have solved several of these issues, and the remaining calibration requirements are often addressed through the use of supporting software packages.

3.2.4.2.2 ACOUSTIC DOPPLER CURRENT PROFILER

The most dramatic innovation in the area of current measurements is a specialized ACM, the Acoustic Doppler Current Profiler, ADCP. In 1981, the scientists of the Coastal Ocean Dynamics Experiment (CODE) requested the design of an autonomous, self-powered, internally recording current profiler. From this request the ADCP, an instrument that was to revolutionize ocean current measurements was born (Williams 2010).

The ADCP is based upon the apparent frequency change of transmitted sound pulses propagating through a moving water mass, and is and example of the Doppler Effect. The Doppler Effect is the change in the observed sound pitch that results from relative motion between an observer and the sound wave. The Doppler Shift is the difference between the frequency of the received sound and the transmitted sound, and is proportional to the change in speed. ADCPs use the Doppler Effect by transmitting at a fixed frequency and listening to echoes from scatterers in the water, whereby the speed of the scatterer, and current carrying them, may be determined. For example, if an object in the flow reflects sound back to the ADCP and the frequency is shifted lower, then the object is moving away from the unit, while an increase would indicate the object moving towards the ADCP. By using three to four transducers arranged either orthogonally or at 120 degrees from each other (Figure 12), and at some angle to the horizontal, the speed and direction of the flow may be determined (Gordon 1996).

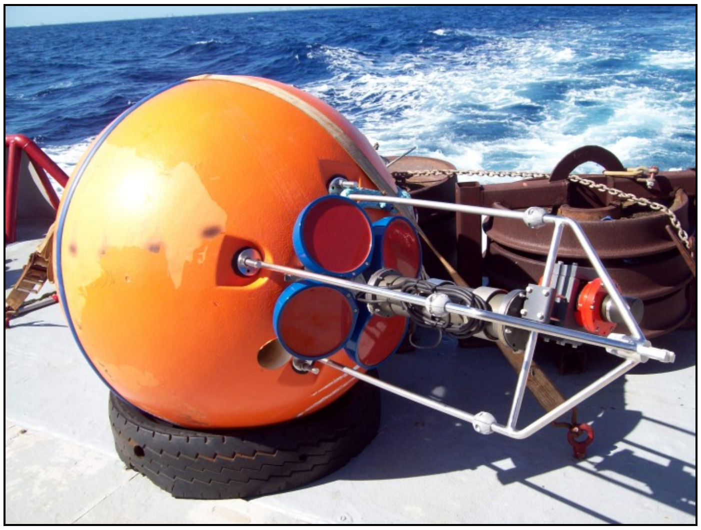

Figure 12. ADCP installed in subsurface mooring buoy (Photo by author)

The ADCP sends a series of acoustic pulses into the water column, either from near the bottom on a mooring or seafloor frame, or from the surface down from a surface buoy or vessel. As the sound moves through the water, it ensonifies a specific volume of water, and the ADCP measures the amount of reflected sound and its average Doppler shift. The amount of reflected sound, or backscatter, provides a measure of the number of scatterers in the volume and how much energy is provided for the measurement. The scatterers include particles in the water, plankton, and in some cases fish. The measurement may be contaminated or blocked by other features, including entrained air bubbles in near-surface deployments. Conversely, the lack of scatterers may result in very low backscatter and correspondingly poor results (Gordon 1996).

The major advantage of an ADCP is not the Doppler determination of water flow, since this technology was common in vessel speed logs long before the ADCP, but the ability to obtain measurements from a single device at multiple locations in the water column.
This profiling feature replicated, and easily surpassed, several point-measurement current meters moored at various depths in the water column. The ADCP samples the return echoes at discrete time intervals, which are related to the distance from the transducer heads, and allows for many different "point" measurements from one device (Figure 13).

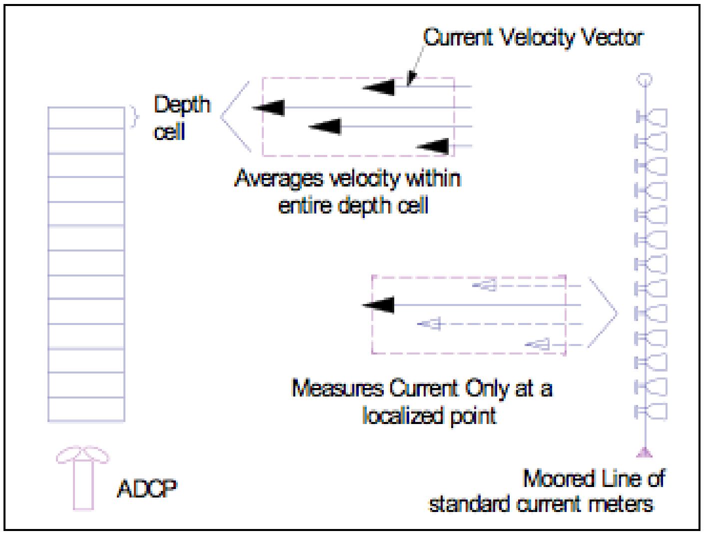

Figure 13. ADCP compared with single-point current meter string (Gordon 1996)

ADCPs have gained in popularity and use by the scientific community as indicated by the trend in scientific papers about the device. This upward trend over the last 30 years indicates how well these technologies have been accepted and used in surveys and other studies, and how they have become the standard against which other devices have been compared (Williams 2011).

While ADCPs are very useful devices, certain aspects of their capabilities must be considered prior to deployment. There are several frequencies available, providing various results. Typically, the higher the acoustic frequency, the higher the vertical resolution. The sampling range, however, is reduced since resolution and range are inversely related. Shallow deployments using a 1.2 MHz transmit frequency may provide velocity every 0.25 m in depth, but only provide a 20 m profile range. A 75 kHz unit may provide a profile range over 600 m, but with current measurements only every 7 to 10 m along that length. These measurement densities are still much higher than the use of discrete current meters and do not require the complex moorings and expensive equipment of previous methods.

Another fundamental characteristic of the ADCP is the inability to measure close to a boundary, either the surface or the bottom, or close to the unit itself. The echo from an acoustically hard surface such as the sea surface or the bottom is much stronger than the relatively weak echoes from scatterers such that the unit can not resolve the Doppler shift or measure the current in those regions. The data within 6 to 15 percent of water depth near the boundary (depending on type of transducer head angle) is normally rejected since side lobes, portions of the transmitted sound pulse that is not used for velocity measurements, can interfere with measurements and often provide invalid information (Figure 14). The governing equation is:

$$R_{\max} = D \text{ x } \mathrm{Cos}(\theta) \qquad (8)$$

Where

$R_{\max}$ = maximum range for acceptable data (m)

D = distance from the ADCP to the boundary (m)

θ = angle of the beam relative to vertical (either 20° or 30°).

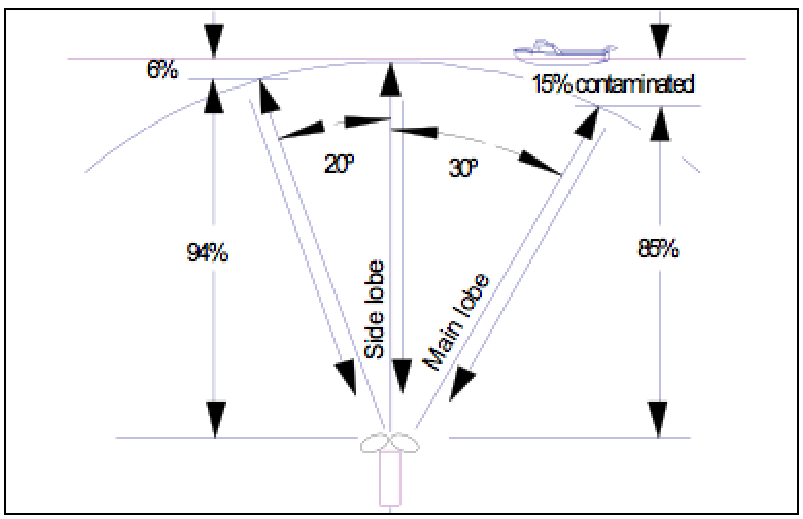

Figure 14. Sidelobe contamination regions for 20° and 30° beam angles (Gordon 1996)

The affect preventing measurements very near the ADCP is transducer ringing. Ringing is where energy from the transmit pulse lingers after the transmit pulse is finished. The physical structure of the ADCP is energized by the pulse and vibrates for a short period of time. Echo signals are weak, and during the ringing any received echoes could be contaminated. The ADCP must pause until the ringing abates before it can process echoes from the water column. This waiting time is called the blanking period, and is dependent upon ADCP frequency. Ringing times are given in distance from the transducer, and indicate the closest point where a velocity may be measured without ring contamination. This range varies from 6 m for a 75 kHz unit to only 0.5 m for a 1.2 MHz ADCP.

These two features are important to consider when attempting to study velocities very close to the surface or seafloor, or placing an ADCP close to the depth of interest. It is better to locate the ADCP some distance away from the depth of interest and boundaries to obtain accurate measurements. In practice, ADCPs are commonly paired with point current meters to obtain data in these specific regions. One manufacturer has integrated three separate transducers that operate at a different transmit frequency than the main transducers and project out from the ADCP housing itself (Figure 15). This provides a measurement of velocity at the depth of the instrument, and in some cases eliminates the need for a separate point current meter (Siegel 2010).

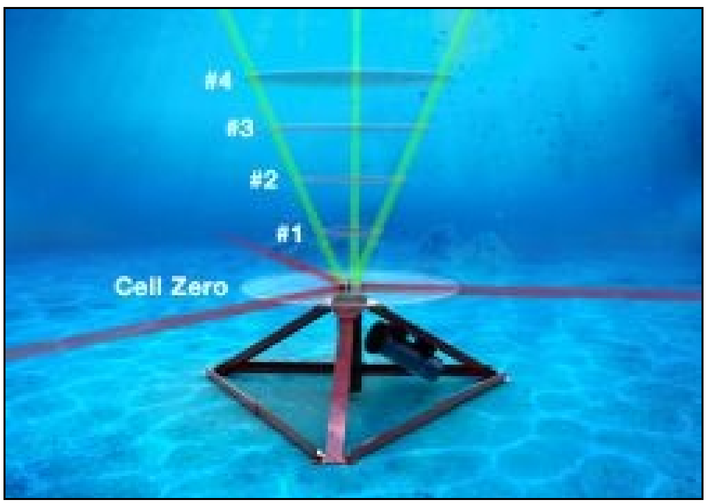

Figure 15. ADCP with horizontal transducers to determine current at unit (Siegel 2010)

Although ADCPs are extremely useful for obtaining previously unattainable velocity profiles due to cost and mooring challenges, the further away from the ADCP the less focused the velocity measurement becomes in terms of a specific location.
Unlike conventional current meters, ADCPs do not measure current in small, localized volumes of water. Instead, they average velocity over the range of entire depth cells. Smoothing the observed velocity over the range of the depth cell rejects velocities with vertical variations smaller than the depth cell, and thus reduces measurement uncertainty (Gordon 1996). This

averaging, however, prevents the ADCP from making small-scale velocity measurements, especially when the small velocity variations of the flow are of interest. A major assumption in ADCP processing is the homogeneity of the water volume at the point of measurement, which in some cases is not valid. The measurement footprint and location may also prevent small-scale features from being detected. For example, at a distance of 300 m from the ADCP, the spatial separation between sampling volumes for opposite beams is 300 m so that they may measure different horizontal regions of the water column that may have dissimilar velocities. For large-scale measurements, locations where moorings would be challenging, and from moving vessels, the profiling capability of the ADCP is an extremely valuable tool for oceanographic research (Emery and Thomson 2004).

3.2.5 OCEAN CURRENT MEASURING RADAR

A practical technique for measuring large areas of surface current remotely has evolved over the last 40 years utilizing a Doppler radar technique, which uses high-frequency (HF) and very high-frequency (VHF) radars utilizing ground-wave propagation (Shay et al. 2002). HF remote sensing is based upon the scattering of electromagnetic waves from a rough moving sea surface, similar to how an ADCP measures water velocity by measuring scattered acoustic energy from particles in the water column. Two radar stations are required, since the received backscatter energy provides only a radial indication of surface motion along the path of the beam. When two radar beams intersect, the radial velocities are composed into vector quantities *v* and *u* for the surface current at that location. The system utilizes a measurement grid with the separation or baseline between radar sites defining the domain of the mapped region (Shay et al. 2002). The grid spacing is dependent upon radar frequency, and ranges from about 0.25 km with a 50 MHz VHF system to about 1.2 km using a 125 kHz HF system (Gurgel et al. 1999, Shay et al. 2002).

Two systems have been used extensively, the Coastal Ocean Dynamics Applications Radar (CODAR) and the Ocean Surface Current Radar (OSCR). More recently, a WEllen Radar (WERA) system was developed expanding on the OSCR system (Shay et al. 2002). The fundamental is the occurrence of Bragg peaks in the spectral patterns of the radar data. As the ocean wave spectrum nearly always contains wavelengths on the order of the radar wavelength, the signals are backscattered from the moving ocean by resonant surface waves of one-half the incident radar wavelength. This generates two distinct Bragg peaks, centered at the one-half wavelength spectrum, and it is the offset of these peaks to the spectrum origin that provides velocity information for an underlying surface current. The equation for determining the Bragg peak of interest (ν_B) of a specific radar system is given by:

$$\nu_B = \sqrt{(g\nu_T/\pi c)} \qquad (9)$$

where

g = gravitational acceleration (9.81 m/s^2)

ν_T = Radar transmit frequency (Hz)

c = Speed of light (3 x 10^8 m/s).

While all of these systems are based on resonant Bragg backscatter, there is a fundamental difference in the methodology used to isolate the ocean area where scattering occurs. If the sea conditions do not contain the radar wavelength such as during extremely calm seas, then there would be no backscatter returns to process the current measurements (Shay et al. 2002). Likewise, during extreme events such as tropical storms, the waves may be so distorted that clear backscatter signals may be unavailable.

The CODAR system utilizes two separate radar sites, with the distance between them related to the grid size of the measured region. The original site configuration consisted of a transmitter antenna and a receive antenna separated at least one wavelength apart. The upgraded systems incorporate the transmit and receive components in the same mast structure, simplifying siting, installation and maintenance. The CODAR system measures radial velocities from each site, and through processing the two radial measurements are combined to create a map of current vectors providing magnitude and direction. The CODAR is known as a direction-finding system, where the azimuthal resolution of the current field is based upon a least-squares fit of the Fourier series to the data (Shay et al. 2002). Velocity resolution tends to be sensitive to beam patterns and must be calibrated prior to use.

The OSCR and WERA systems utilize a multiple element phased-array antenna to achieve a narrow beam, electronically steered over the radar-illuminated ocean area. The beam width is a function of the radar wavelength divided by the length of the phased array. A typical example uses an antenna spacing of 7m for the HF mode using 16 antennas and 3.5m for VHF mode using 32 antennas. The length of the resulting antenna array is 112 m, and can pose installation issues related to obtaining land use permission, as well as identifying an area large enough and also free of physical and electronic obstructions such as buried and above ground power lines and metal-fabricated structures. The relative distance between antennas and amount of clear area required for each system type are significantly different (Figure 16). Newer CODAR systems only require one mast which includes the transmit and receive elements.

 

Figure 16. CODAR two-antenna (left) and WERA receive antennas (right) (Photos by author)

Issues with radar current measuring systems include sources of interference, siting constraints, sea surface conditions, and issues with supporting hardware. As all HF and VHF radar antenna systems have a characteristic beam pattern, environmental factors such as salinity, soil moisture and path length from the antenna to the sea influence the beam pattern. Proper system calibration to identify and compensate for any interferences is essential to proper operation. Siting constraints may be challenging and unlike at-sea measurement systems, radar sites are usually accessible by the general public and sometimes subject to vandalism or innocent damage. Sea surface conditions may also affect measurements. While the system depends upon a relatively rough sea surface for backscatter, in some cases rough seas may actually degrade performance. One study indicated that at near ranges higher waves cause higher signal strength, while at intermediate ranges the opposite was the case, suggesting working range decreases with increasing sea state. Possible reasons for this behavior are most probably noise induced by other processes than Bragg scattering, such as shadowing effect or signal absorption by sea foam (Gurgel et al. 1999).

3.3 COMPARISON OF CURRENT METER TYPES

A current meter is capable of accurately recording only a portion of the total water column because of influences from mooring type, velocity sensor used, and the sampling and recording scheme of the instrument. Current meters are typically calibrated under flow conditions nonexistent in the ocean (e.g. fastened to a rigid mount in a steady state flow regime rather than on a flexible mooring line in flow containing a myriad of temporal scales) (Halpern et al. 1981). In situ comparisons of various types of current meters are important to determine the best and worst case conditions for the application of a specific type of meter.

A surface-following float inevitably moves in all directions, and current meters suspended beneath it detect the motion. The effect on the current measurement depends on the mooring configuration, the type of current meter, and the environmental conditions of wind, waves, and current. A sub-surface mooring is located far below the surface and most effects from wind and waves, and usually provides a more stable platform for sensor installation. In regions of high current, however, the challenges of sub-sea moorings are as daunting as those for surface moorings, and in some cases more so since a sub-surface mooring must rely on compact size for drag reduction while maximizing buoyancy to remain vertical. A surface buoy may be much larger than required, since hydrodynamic drag only affects a portion of the buoy, therefore providing much more reserve buoyancy to maintain the mooring. In general, however, sub-surface moorings are preferred for current and other oceanographic measurements.

The comparison of a VACM, VMCM, and ACM on surface and subsurface moorings was conducted (Halpern et al. 1981), and determined that 1) above the thermocline at depth from 5 to 27 m a spar buoy is recommended for a VACM while the VMCM and ACM may be used with a surface following buoy, and 2) below the thermocline between 79 and 94 m better quality is obtained with all three types when deployed on a subsurface mooring with the flotation below the influence of surface waves. The difference in current meter low-frequency current amplitudes was 2 times smaller in strong currents than when the flow was weak. This may be attributed to the larger horizontal velocities compared to vertical velocities in higher currents, while during low flows the vertical, wave induced velocities are more pronounced in the resulting measurements.

Another comparison study included electromagnetic current meters (EMCM) as well as the standard mechanical current meters, and determined that only VMCM and EMCM type meters were capable of producing quantitative velocity measurements on a surface mooring in the presence of a moderate wave field. The other current meters located near the surface showed large differences in performance due to limitations in design and/or sampling techniques. Current meters moored at sufficient depth to be free of the influence of surface waves, however, were in good agreement, typically between 2 and 5 cm/s with each other (Woodward et al. 1990).

Winant et al. (1994) compared a surface buoy-mounted ADCP with a nearby string of VMCM current meters of the coast of San Diego, California to determine the relative agreement between the two methods. The buoys were deployed for about 18 months, and experienced a wide range of environmental conditions. While ADCPs had been used extensively on ships that are subject to significant rolling motion, their use on more severe-acting surface buoys was of concern, especially since the ADCP compass only functions reliability at tilt angles less than 20°.

The comparison suggested that the ADCP and VMCM units produced accurate horizontal current profiles when wave-induced buoy motion was not overly large. During large surface waves, however, the ADCP usually reported erroneous results. In addition, the mean vertical velocities from the ADCP during these conditions exceeded values that could be physically expected, and were deemed unreliable. In general, with the exception of severe weather events, the two systems seemed to agree, and the ease of ADCP installation compared to the multi-unit VMCM meter mooring suggested the potential of obtaining long-term time series of currents in a more efficient manner (Winant et al. 1994).

A comparison between CODAR current measurements with an array of moored current meters was conducted by Emery et al. (2003). A network of five 13 MHz CODAR systems was operated off Santa Barbara, California and collected data for the same period as a large array of current meters. The radar coverage area included eight current meter moorings from 1993 to 1999. The moorings utilized VMCM meters at 5 and 45 m depths providing hourly averages of current velocity.

An accepted overall indicator of radar performance is spatial coverage over time, which is defined as the number of sectors returning radials each hour. Coverage variability during the experiment included power outages, antenna collapse, other hardware failures, and even a partial cable bite-through by nosey rodents. Gaps for vector averages were less frequent, however, due to the overlap of adjacent radar systems in the area. The following conclusions were made of the comparison:

1. Radials obtained from the radars were significantly correlated with the radials determined by the moored current meters with correlation coefficients ($r^{2)}$ in the range 0.39 to 0.77. A weak trend of increasing rms difference was found with increasing radar range.
2. Significant coherence was found between current meter and radar time series for frequencies below 0.1 cph (10 hour period and longer)
3. Pointing errors $\Delta\theta$ for the radars ranged from -16° to +19°, and were speculated to result from distortions of the receive antenna patterns in the near field, phase calibrations, or properties of the processing software.
4. Using a uniform flow model parallel to shore the pointing error $\Delta\theta$ produced speed errors up to 15% and direction errors up to 9° in total velocity errors.

4. FLORIDA CURRENT STUDIES

4.1 PILLSBURY EXPEDITION

The Florida Straits is one of the most studied areas of ocean currents due to the logistical ease of access. Its close proximity to shore and relatively narrow channel allows for detailed and continuous measurement and study. The first comprehensive scientific measurements of the Florida Current portion of the Gulf Stream system were made by the United States Coast and Geodetic Survey between 1867 and 1889. In 1885, 1886, and 1887 Lieutenant J. E. Pillsbury moored the survey vessel Blake directly in the axis of the Florida Current to make direct measurements of the direction and rate of flow using a current meter of his own design. The main purpose of this expedition was to determine the volume of transport through the Florida Straits, and its contribution to the total flow and character of the Gulf Stream system. The Gulf Stream was considered vital to trade and the prosperity of the United States, and as such required study and quantification. The primary question of the expedition was:

> What is the surface strength of the current and what is the direction of the flow? It is well known that these vary at many if not at all parts of the stream. Can a fair knowledge of these variations be predicted? (Pillsbury 1891).

Pillsbury sought to answer this question by mooring his vessel directly in the Florida Current at several locations and measuring the flow velocity at a variety of depths to determine not only the surface flow but also the vertical distribution the total flow through the Straits.

Pillsbury made six major transects across the Florida Current and portions of the Gulf Stream, although only two, Sections A and B, were directly in the Florida Straits. Section A crossed from Fowley Rocks near Miami, Florida west to Gun Cay, Bahamas near Bimini, at approximately 25.5° N, while Section B crossed between Jupiter Inlet, Florida to Memory Rock, Bahamas at approximately 27° N. Section A was the most comprehensive transect, with a total of 1,110 hours of observations, the longest continuous measurement lasting166 hours (almost 7 days). The measurements were made at 3.5, 15, 30, 65, and 130 fathoms (6.4, 27.4, 54.9, 118.8, and 237.7 meters) at six locations across each section.

Pillsbury discovered the monthly flow variations in the Florida Current, which involved a deepening of the current core at times, while at others it diminished at depth but increased in velocity along the sides. He also determined the magnitude of the tidal variations on mean flow, which at times was nearly 1.3 m/s above or below average, and observed "rips", sudden increases in velocity during favorable wind conditions. Both types of variations were noted much higher on the west side of the stream, an indication of the geostrophic aspect of the flow.

He determined the volume of the stream was best determined at his Section A, where is is confined in width "by earth instead of water walls" (Pillsbury 1891) and where practically all of its water flows into the Atlantic. At section B he surmised that there might be an eddy current along the Little Bahama Bank and inflow through the Northwest Providence Channel that would affect volume measurements at that location. He based his calculations upon a layer of zero motion at 130 fathoms (237.7 m), the extent of his measurement capabilities, and assumed no flow in the deeper regions of the Straits. His volume transport result through section A was therefore 89,872,000,000 long tons of water per hour, or in modern units about 24.9 Sv, and that almost one-half of this volume was carried within the upper 100 fathoms (182.8 m) of the surface. Interestingly, Pillsbury was the first, and until the advent of more advanced measurement techniques such as ADCPs and radar, the only researcher to obtain such high accuracy of the Florida Current near-surface (< 150 m) velocities due to his surface-based measurements from an anchored vessel. The drawbacks of this approach, however, were the large hydrodynamic forces on his equipment while deployed in the torrent, which prevented him from full depth measurements.

This pioneering dataset enabled a convincing demonstration of the correctness of later methods used for computing relative currents in regions where the flows were too small to be measured with current meters or where the water depths prevented a stable measurement platform (Sverdrup 1970). The results indicated (Figure 17) a close agreement between measured and calculated velocities in the Florida Current based on Pillsbury's data from the 1800's.

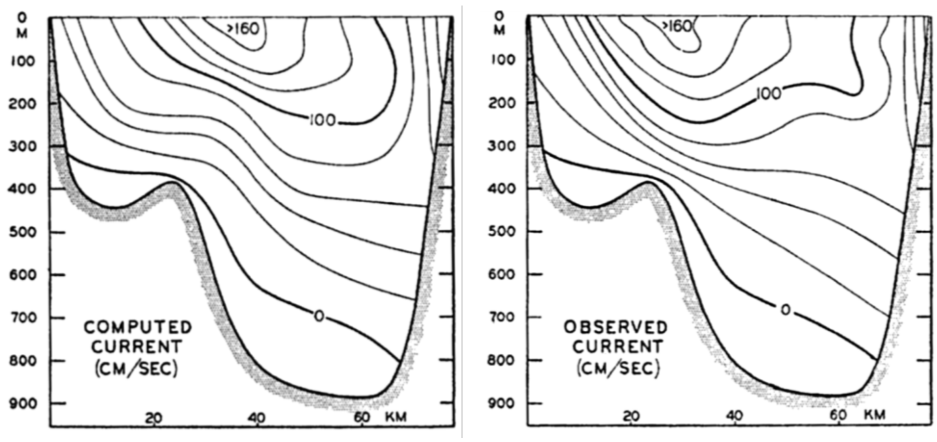

Figure 17. Calculated (left) and measured (right) velocity profiles for the Florida Straits (Sverdrup 1970)

4.2 SCHMITZ AND RICHARDSON

Aside from the Pillsbury measurements in the 1880's, the earliest modern observations of the Florida Current structure were made using dropsondes between 1964 and 1970. Over the seven-year period a total of 75 complete dropsonde sections were taken, each involving up to 13 dropsonde sections across the Florida Straits between Miami and Bimini Island, Bahamas, along about 26° N (Meinen et al. 2010).

The dropsonde study conducted by the Physical Oceanography Laboratory at Nova University measured the vertically averaged horizontal flow of the Florida Current at four sections along the Florida coastline, with approximately 10 stations per section, at non-uniform spacing varying between 3 and 10 km. The main objective of the study was to determine the Florida Current transport volume by demonstrating the feasibility of direct measurements of a major oceanic current system. Tidal and other periodic fluctuations were studied, with an attempt to define which tidal components and/or oceanographic influences caused the flow variability (Schmitz and Richardson 1968).

Sampling was initially conducted sequentially from station to station, although later stations were sampled more rapidly by conducting partial transects and moving back and forth between stations. This procedure allowed for more detailed information of small temporal flow variations. The combination of complete and partial transects provided quasi-synoptic total transport measurements. Sections II and III were used for transport calculations since the sections provided no means for additional water addition or subtraction to the flow. Transport across both sections agreed to within 1~3%, with 1% of the difference attributed to numerical integration error. The resulting mean transport was about 32 Sv averaged over all 33 station and seasonal combinations (Schmitz and Richardson 1968).

The study compared findings with the Pillsbury transport value of 24-26 Sv, and determined that within the upper 130 fathoms both studies agreed within 10 percent. Furthermore, given the ability of the dropsonde to measure the entire water column, and the discovery that there is no level of zero flow in the Florida Straits, the Pillsbury data was recalculated using full depth values instead of the assumed zero flow level at 130 fathoms. The resulting full-depth transport values also agreed within 10 % over the 70-year interval separating the two sets of measurements, suggesting that the Florida Current average transport has remained stable between studies.

Fluctuations in transport were found to occur most often (about 75% of the range) at frequencies above 10^{-1} cycles per day (c.p.d.) and that at least 50% of the range was associated with a frequency band of about 1 c.p.d. Short, rapid (compared to 1 sample per day) measurements were obtained, and indicated barotropic fluctuations at frequencies higher than 10 c.p.d have amplitudes within experimental error (approximately 1% of total transport ~ 0.327 Sv), and that tidal motions are relatively energetic. The net fluctuation bound was observed to be +/- 12 Sv, while complex tidal amplitudes were 3.5 +/- 1 Sv for M_2 (12.42 hr), K_1 (23.93 hr), and O_1 (25.82 hr), and 1.5 +/- 1 Sv for S_2 (12.00 hr). The relative magnitude of tidal variations agreed with the Pillsbury study, and indicate tidal forces are a significant contributor to Florida Current transport variability on a relatively short timescale (Schmitz and Richardson 1968).

The limitations of the dropsonde current measurements conducted by Nova included vertical averaging with no level discrimination, they were not continuous, and were not truly synoptic measurements. Mean transport and average fluctuation was determined and agreed with previous measurements, yet the stratification and relative contribution of various flow levels was not possible.   The average transport of 32 +/- 3 Sv was the first accurate value utilizing the full extent of flow in the Florida Straits, and became the standard for comparison with later studies.

4.3 SUBTROPICAL ATLANTIC CLIMATE STUDIES (STACS)

The Subtropical Atlantic Climate Studies (STACS) program was conceived in the early 1980's to increase the understanding of oceanic circulation and its role in establishing global climate (Molinari et al. 1985). The program began with an intensive monitoring effort of the Florida Current, and consisted of several moored current meter strings, dropsonde measurements, subsea cable measurements, radar, and tide gauges. The objectives of the STACS program were:

1. Determine the global distribution of meridional ocean heat flux by studying transport through the Florida Current
2. Provide a base set of data to provide constraints to and verification for developing general circulation models (GCMs)
3. Develop the technology to monitor climactically important oceanic processes
4. Begin monitoring operations for long-term climate studies

The North Atlantic Ocean was selected for the focus of STACS because research indicated a larger poleward heat flux in the basin than in the North Pacific, and the largest signal in oceanic heat flux apparently occurs across the latitude band 20° N to 30° N, the region of the subtropical gyre in the North Atlantic. By focusing STACS at about 27° N, and within the readily accessible Florida Current, the program objectives were further focused upon a region with important contributions to meridional heat flux (Molinari et al. 1985).

STACS activities initially focused on the Florida Current and its role in heat flux based upon previous studies, and the objectives were to develop the capability to monitor the annual cycle and interannual variability of the current's volume and temperature transport. A major question was whether the Florida Current could be used as an "index" for basin-wide air-sea interaction with regard to heat transport. To meet the initial objectives of STACS, a 2-year intensive observing period was initiated in April 1982, and included direct and indirect methods. Direct observations of Florida Current temperature and volume transport were made by ship-deployed current profilers (Pegasus dropsondes) and moored current meter arrays (mechanical current meters). Indirect methods included transport measurements from a subsea communications cable, a coastal radar station, and tide gauges on either side of the current (Figure 18).

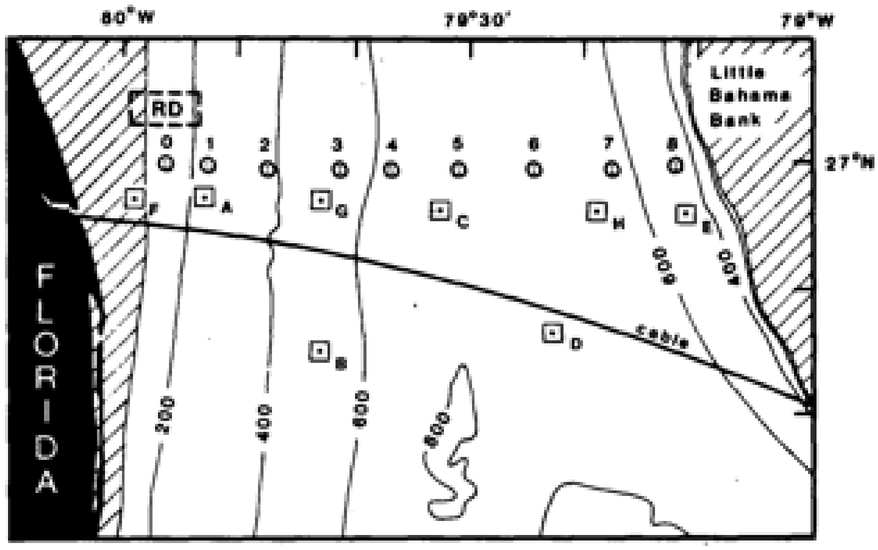

Figure 18. STACS equipment locations (Circles Pegasus stations, squares current meter moorings, subsea cable, radar area RD) (Lee et al. 1985)

The STACS program results showed for the first time a combined series of measurements and various devices could provide calibrated and continuous observations of mean Florida Current transport that correlated moored and profiling measurements. This suggested that direct observations could be phased out, freeing resources for studies other than heat flux processes (Molinari et al. 1985). These methods only measure mean transport, so short temporal events such as turbulence and stratified current measurement would still require direct measurements.

The STACS project produced a large volume of current and temperature data, as well as information on wind, pressure, and water level for the Florida Current. This database enabled a large number of follow-on studies and resulted in a much better understanding of the Florida Current and its characteristics, as well as important features relevant to its heat transport capabilities. The data sets also provide invaluable time series for validating numerical models and use for long-term transport comparisons (Molinari et al. 1985).

Using the STACS data, large-scale meanders were discovered and quantified. Johns and Schott (1987) determined that approximately one-fourth of the total sub inertial velocity and temperature variance contained in the STACS data was associated with Florida Current meanders (Figure 19). Coherent, energetic meandering signals were found at two limited frequency bands centered near five and twelve days. The energy transfer analysis concluded that, even though in close proximity within the Straits of Florida, the energy off Miami at 25° N appears to be transferred quite strongly from the mean flow to the meanders, whereas at 27° N offshore West Palm Beach the net energy flow appears to be from the meanders to the mean flow, suggesting that the overall stability of the Florida Current may be different at the two locations (Johns and Schott 1987). This is important since the region from 25° N to 27° N has historically been the focus of transport studies due to the geographical constraints of the channel and the few locations for water addition to the flow, such as through the Northwest Providence channel (Schmitz and Richardson 1968).

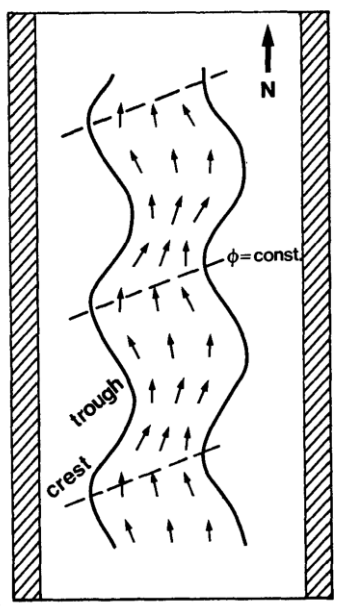

Figure 19. Composed waveform illustrating Florida Current meander crests and troughs (Johns and Schott 1987)

The meanders are northward travelling waves with upwelling occurring in the troughs between the offshore meander and the shelf break. The cool upwelled water moves northward with the meander wave as a cyclonic frontal eddy that in turn interacts with the Florida Current by dragging, or detraining a warm filament around its onshore side (Fiechter and Mooers 2003).

Another study based upon STACS data investigated the role of wind stress in the fluctuations of transport in the Florida Current. The data indicated a strong connection between transport variations in the 2 to 10 day period band and local meridional wind stress. A simple analytical model was developed to determine the relationship between both meridional and zonal wind stress with observed flow response based upon STACS observations (Lee and Williams 1988).

The STACS moored current meters were deployed at several locations across the axis of the Florida Current, near 27° N latitude. Due to engineering constraints on mooring design and a desire to obtain good mooring performance, the moorings extended upward to only about 150 m from the surface in the high velocity regions of the current. Two types of mechanical current meters were used, the Aandrea Recording Current Meter (RCM) and the Niskin Winged Current Meter (Johns and Schott 1987).

One objective of the moored array measurements was the calculation of transport time series, yet this was hampered by the need for interpolations and extrapolation of data from an array that covered only part of the water column. The simplest approach was extrapolation of the current profiles at each station to the surface using the most realistic extrapolation profile (based upon Pegasus measurements), and then multiplying the transport per representative unit width (Schott et al. 1988).

There was a significant seasonal change in the local wind forcing, with much higher energy in winter at periods of several days (cold front passages) than in summer. Wind speed was adjusted by a factor of two to produce oceanic winds from coastal winds to calculate wind stress, which used a constant drag coefficient of 1.5×10^{-3} (Schott et al. 1988). The current meters were located below the surface Ekman layer, so the calculated vertical cross-channel flow was 180° out of phase with along-channel wind stress. The wind-induced flows could be observed at the deeper moorings, although the velocities were low and often masked by meander motions (Lee and Williams 1988).

Due to the paucity of downstream information in the STACS dataset, only the classical cross-stream exchanges based upon quasi-geostrophic instability theory were considered as an indication of either barotropic or baroclinic instability in the Florida Current. This approach assumes that the mean flow has no downstream variation, which based upon the data is most likely not true of the Florida Current. Without sufficient density of downstream measurements, however, this was the most suitable approach (Johns and Schott 1987).

4.4 *EXPLORER OF THE SEAS* ADCP STUDY

Between May 2001 and May 2006 an ADCP was installed within a cruise ship to obtain repeated measurements of the Florida Current near Miami, Florida. Using the vessel *Explorer of the Seas* five years of full-depth velocity data was collected across the Straits at 26° N, and the data was compared with transport values determined from a subsea cable at 27° N offshore West Palm Beach, Florida. The cruise ship transport, 31.0 +/- 4.0 Sv, compared with the cable voltage transport of 32.4 +/- 3.2 Sv, indicating an input from the Northwest Providence Channel of an average of 1.4 Sv into the Florida Current. The climatological core of the Florida Current was found at 79.8° W, with an average velocity of 1.7 m/s (Beal et al. 2008).

Two vessel mounted ADCPs were used, a 38 kHz unit with a nominal range of 1000 m to profile the entire water column across the Straits, and a 150 kHz unit with a typical range of 300 m that allowed for better vertical resolution of the highly-sheared surface flows. The 38 kHz unit had a resolution of 24 m with a top cell at 36 m depth. The 150 kHz data was use to determine the best interpolation algorithm to extend the 38 kHz unit data to the surface. Due to issues with ADCP signal attenuation, navigational equipment, and equipment conflicts, the anticipated level of detail was not realized. The mean transport, however, did agree with the “standard” values of the subsea cable within acceptable limits, and provided a good determination of the relatively constant “core” of the Florida Current. This core was found to be close to the western shelf break with velocities over 1.7 m/s. The core was found to move offshore with depth, as is typical of a western boundary current and consistent with the findings of both Pillsbury and Richardson in earlier studies. The greatest variability of the Current was found over the Miami Terrace and shelf break, probably as a result of meanders associated with high horizontal shear (Beal et al. 2008). The top 100 m of the current also exhibited larger variability over much of the section and could represent a direct wind-driven response as described by researchers from the earlier STACS experiment.

The *Explorer of the Seas* ADCP program posed some unique challenges compared to similar installations on research vessels. The two largest sources of error were inaccurate heading information and bubble entrainment over the transducer faces. These factors contributed to errors in the cross-track and along-track components of velocity. A third was the low ping rate used to collect the data (Beal et al. 2008). The average speed of the vessel was over 10.3 m/s (20 knots), more than twice that of typical research vessels. This speed both enhanced heading errors due to the rapid changes in position, and increased bubble contamination due to turbulent water flow at the high speed over the ship's flat-bottomed hull. These bubbles blocked acoustic signals and biased velocity values due to their movement across the hull and transducer faces. Contamination tended to be high during periods of acceleration/deceleration and changes of heading, as well as during rough seas when the hull entrained bubbles by nature of its flat bottom.

Most data was contaminated, but fortunately acoustic energy did penetrate to the lower depths and useable data was collected. Many good pings were lost due to the occurrence of a few bad pings in the averaging period, yet a method of processing single ping data instead of the typical ping averaging procedure recovered approximately 40 percent of the data.

A final factor in the quality of the *Explorer of the Seas* dataset was the large time separation between pings, which lowered the number of data points for processing and made the data collected more susceptible to contamination. The two ADCPs, operating at 38 and 150 kHz, were not operated at the same time because of potential interference. The units were "slaved", where the 38 kHz unit would transmit, and after a wait period of approximately 16 seconds, the 150 kHz unit would transmit and collect its data. This resulted in time between pings of almost three times that of research vessels, with a resulting random error of about 1.6 times greater (Beal et al. 2008). Since the study, procedures were developed which vary the ping cycles of the two units so interference is minimized while faster ping rates are used.

Despite the technical issues encountered, the resulting dataset confirmed earlier transport estimates, and provided interesting insight into near-surface flow structures. The averaged Florida Current profile (Figure 20) has become a standard for researchers and other parties in project planning and model validation.

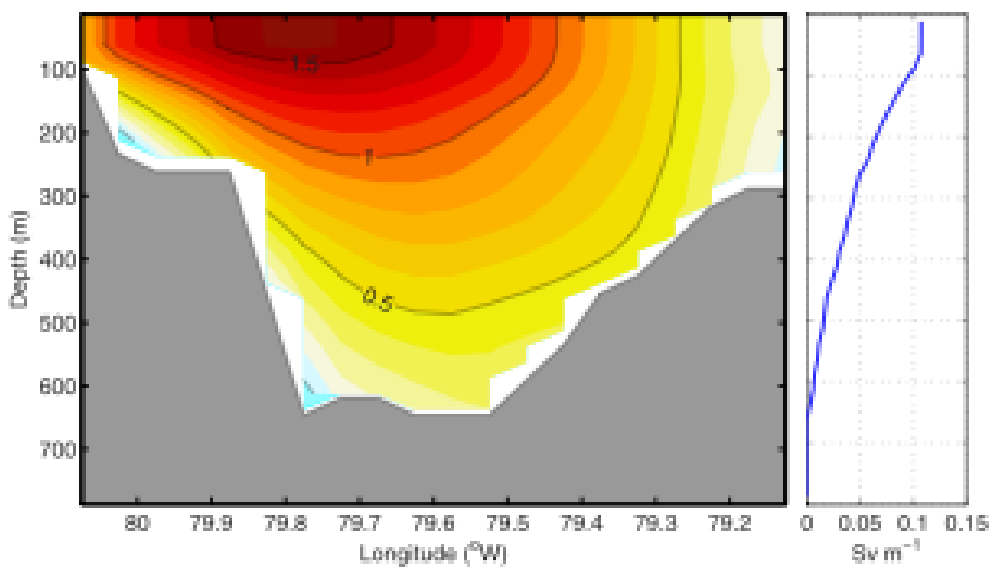

Figure 20. *Explorer of the Seas* Florida Current mean velocity profile (Beal et al. 2008)

This project provides a sound example of how proper planning and utilization of different equipment must be defined prior to implementation. Since May 2006, with the addition of a GPS sensor and modified ping management, the velocity data has been greatly improved. Unfortunately, shortly afterwards the *Explorer of the Seas* moved from its home port in Miami to its new port in New Jersey, so the program was terminated for the Florida Current.

4.5 SFOMC RADAR STUDY

An ocean surface current radar (OSCR) study was conducted off Dania Beach, Florida by Shay et al. (2002) in support of the South Florida Ocean Measurement Center (SFOMC) in the summer of 1999. The OSCR system was operated for a 29-day period along with a coincident deployment of three ADCP arrays (11, 20, and 50 depth contours) and periodic shipboard ADCP measurements. The system consisted of two VHF transmit/receive stations operating at 49.945 MHz that detected surface gravity waves with wavelengths of 2.95 meters. The measured spatial domain was a 7 km x 8 km area with a horizontal resolution of 250 m at 700 grid points. The alongshore baseline between stations was 6.7 km, and each site consisted of a four-element transmit and thirty-element receiving array (spaced at 2.95 m). The area of study was fairly close to shore compared to other Florida Current measurement programs, but the importance of the study indicated the effects caused by intrusion of the Florida Current in shallow waters along the edge of the flow, and the resolution of surface velocities available from radar measurements (Shay et al. 2002).

Radar observations produced good coverage of the study area, and included an intrusion of the Florida Current. Surface velocities 5 to 7 km offshore exceeded 1.4 m/s with a large surface current gradient near the shelf, while closer to the coast surface currents were between 20 and 30 cm/s. The current regime within the study area changed within hours due to the movement of the Florida Current into the region, indicating several surface current rotations. These measurements exemplify the dynamic coastal regime along the edged of the Florida Current. A notable difference between flows outside the shelf break, where currents exceed 50 cm/s consistent with the proximity to the Florida Current, and the flows inshore of the break between 10 to 20 cm/s indicate how bathymetry contributes to the dynamics of coastal flow near a strong current (Shay et al. 2002). The time-averaged estimates suggest substantial cross-shelf variability in the along-shelf surface current structure as indicated by the red vectors pointing out of the study area during the 4-day period (Figure 21). Atmospheric conditions were monitored during the experiment and did not indicate either surface winds or waves significantly impacted the surface velocity field compared to oceanic forcing induced by Florida Current intrusions across the shelf break.

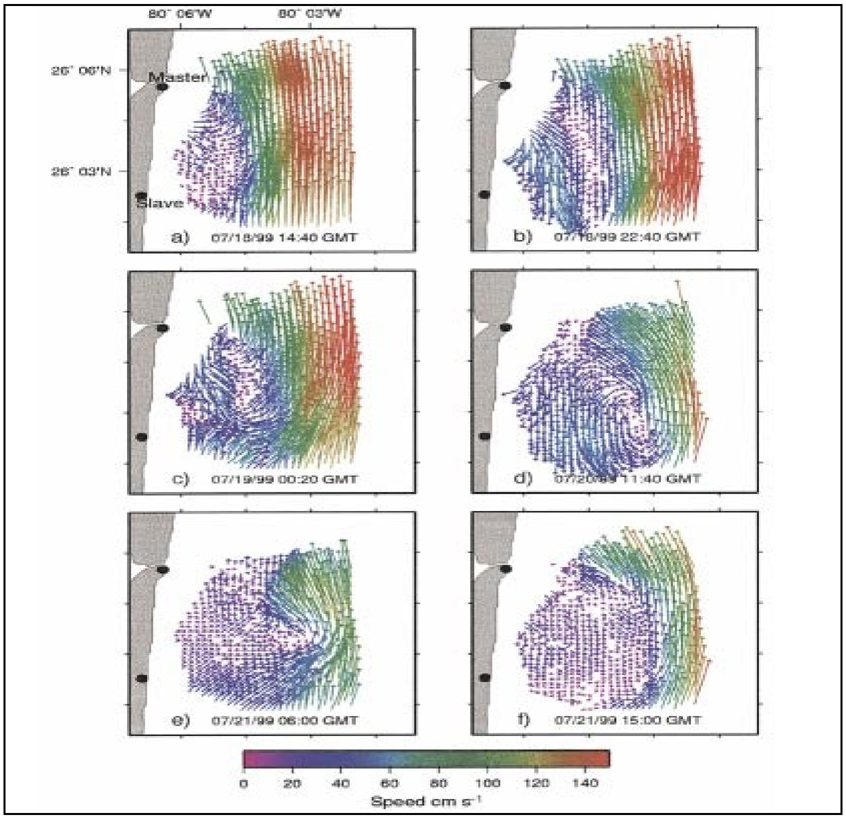

Figure 21. OSCR surface current measurements from 18-21 July 2000. Colors represent magnitude. (Shay et al. 2002)

The radar data was compared with moored and vessel-mounted ADCP units during the measurement period. The velocity values from near-surface ADCP bins were compared with the surface velocities from the radar system and processed using regression analysis from the subsurface to surface velocity values. The results indicated that the measurements in the upper few meters (3.2 and 4.2 m depths) of the water column at the 50 m mooring were quantitatively consistent with the radar surface currents. Comparison with vessel-mounted ADCP measurements was similar, with current differences normally distributed within the 95 percent confidence limits. The correlations between ADCP and radar velocity measurements exceeded 0.8 provided acceptable agreement between the two measurement methods (Shay et al. 2002).

Issues identified during the project included the large coastal area required to install the four transmit and 30 receive antenna arrays and the limited offshore range (8 km) required to obtain fairly high (250 m cell) resolution at the 49.945 MHz operating frequency. Other radar systems, such as CODAR, do not require the large antenna arrays, but may have other issues that are not relevant using the OSCR system (range-finding versus beam forming techniques). The range versus resolution issue is common for all radar system types, and installation location, geometry, and frequency selection must be considered to obtain desired results.

5. CONCLUSION AND RECOMMENDATIONS

5.1 CHALLENGES

The Florida Current has long been of interest to oceanographers due to its importance to the general North Atlantic circulation and its role in global heat transport (Molinari et al. 1985). A large number of studies have been conducted to determine the mean water transport through the Florida Straits, specifically between 25° and 27° North latitude. This region of the Straits is confined between the Florida peninsula and the Bahamas and the addition of water is restricted with the exception of some input from the Northwest Providence Channel above 26° N.

Although many studies have determined the mean transport of the Florida Current, almost all of them used interpolation or some other means to obtain water velocity in the upper 100 m of the current. Two inquiries directly measured flow in this region, the Pillsbury expedition in the 1880's (Pillsbury 1891) and the acoustically tracked Pegasus dropsondes used during the STACS study (Molinari et al. 1985). Even these efforts, however, provided a few discrete measurements at a specific depth or a velocity profile obtained by a few acoustic fixes during the short amount of time the dropsonde sank or ascended through the upper 100 m. Neither method provided high spatial resolution or an extended time series of current behavior in this region.

The two elusive measurements in the upper depths of the Florida Current are high-resolution profiles (velocity versus depth) and long-term but high temporal resolution (minutes to hours) time series of current behavior. This information is important to climate study to accurately determination global heat transport and for ocean energy developers who intend to use the highest velocity portions of the current to generate electricity (Van Zwieten et al. 2013). Pillsbury (1891) indicated that almost half the transport occurs in the upper 100 fathoms (182.8 m) of the surface, which agrees with more recent estimates and profiles of the current.

The reason it is difficult to measure the upper level of the current is precisely the feature of interest, the very high (greater than 2.5 m/s) water velocities and variable vertical shear profile (velocity change over depth). These flows have hampered transport studies and limited the depth of current meter moorings to within 150 m of the surface in the center of the current (Lee et al. 1985). Likewise, cruise ship ADCP measurements were only obtained starting at 36 m depths due to blanking period, since a frequency of 38 kHz was needed to profile the entire depth of the Straits. Although within the upper 100 m level, the measurement bins were spaced at 24 m and operated at a slow ping rate, resulting in only 3 measurements in that region at fairly long sample intervals (Beal et al. 2008). Surface current radar has obtained surface velocities that are theoretically coupled to subsurface velocities down to the upper few meters, with correlation values when compared to ADCP measurements of about 0.8 (Shay et al. 2002). At radar frequencies that can cover the core of the current, approximately 19 to 32 km offshore, the cell spacing is on the order of kilometers, with currents averaged within each cell. Drifters are of some use in measuring short-term surface velocities, but unless they are expendable, the cost and time of recovery and redeployment prevents their feasibility given the short residence time in the Straits due to the high velocities, advecting the devices northward up to 216 km/day.

5.2 RECOMMENDATIONS

The issues related with obtaining current measurements in the Florida Current are clearly described in previous studies, including methods to reduce the effect of the flow and stabilize measurements. The mooring used during STACS utilized fairing, a type of covering placed on the mooring cables in an attempt to lower their hydrodynamic drag, one of the major environmental factors that hinder buoys in high flows (Lee eta al. 1985). The higher the water velocity, the larger the force, or drag (F_D), on the object becomes as the square of the velocity, given by the equation:

$$F_D = 0.5 \text{ x } C_D \text{ x } \rho \text{ x } u^2 \text{ x } A_p \qquad (10)$$

where

C_D = drag coefficient based upon both velocity and shape

ρ = density of seawater

$\boldsymbol{u}$ = velocity (m/s)

A_p = projected area of the object (m^2).

As more cable is required, and the larger the buoy, the larger the forces are upon the mooring. Cable fairing attempts to reduce the C_D, thereby reducing the drag somewhat. A more substantial approach is to use a buoy of a hydrodynamic shape similar to an airship hull instead of a typical spherical buoy. A streamlined ADCP buoy was deployed in the Gulf Stream by Johns (1988) and resulted in a steadier measurement platform within the higher velocities near the surface. This design (Figure 22) not only reduced the C_D but also the projected area A_p, and therefore had a more significant impact on drag reduction.

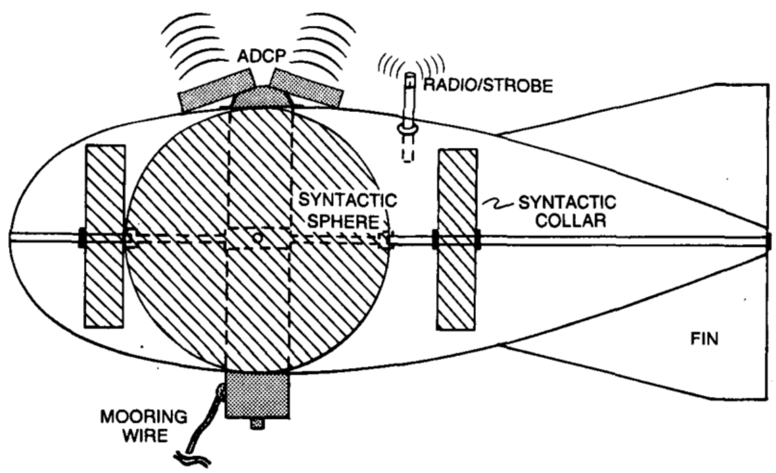

Figure 22. Streamlined ADCP float used in Gulf Stream studies (Johns 1988)

The results indicated that the C_D for the streamlined float was approximately 0.2, while for a similar-sized sphere it was approximately 0.6 (i.e. the comparable drag was reduced by a factor of about 3) (Johns 1988). This low drag buoy approach is a possibility for Florida Current measurements, but the design would require consideration not only of reduced drag but vertical stability and longevity, something not critical during the 6-day Johns deployment.

Besides the measurement platform, other considerations would be needed, such as type of sensor to use. The frequency versus range issue with ADCPs and the surface contamination from side lobes described by Gordon (1996) is of concern with the use of an ADCP. In order to obtain high vertical resolution, less than 1 m ideally, a high frequency device in the range of 300 kHz with a range of 100 m would be required, although the standard deviation for a one-meter bin size is 6.3 cm/s, whereas for a 2 m size it drops to 3.2 cm/s (Gordon 1996). Using a 20° transducer angle, the contaminated data would eliminate the upper 6 m at 100 m from the surface. Also, since the ADCP averages velocities over a set time interval, the stability of the measurement platform, as described above, would be a substantial factor in the quality of the averaged results. An ADCP moored within 100 m of the surface, however, could provide a substantial amount of information regarding the upper flow regions in the current, but would lack the upper 6 to 10 m just below the surface.

While a subsurface mooring tends to be more stabile than a surface-following buoy (Halpern et al. 1981), access to the near-surface velocities are difficult to obtain with a subsurface instrument. Pillsbury (1891) was able to measure currents at 3.5 fathoms (6.4 m) from his surface vessel while moored within the current. While an ADCP could be used, given the blanking period required, between 0.5 to 2 m for 1200 kHz and 300 kHz systems, respectively, and the draft of a surface buoy of approximately 1 m, the upper 2 m would not be measured. Additionally with ADCPs, the high flow would tend to entrain bubbles under the buoy, similar to issues encountered during cruise ship measurements (Beal et al. 2008). A non-acoustic sensor, such as an electromagnetic current meter (EMCM) could be deployed very near the surface and obtain reasonable measurements, even in waves (Woodward et al. 1990). Periodic drifter deployments over the location of the subsurface sensors could also provide validation of surface current estimates made from measurements a few meters under the surface. Of course, surface current radar systems, at a more coarse scale, could be used to determine larger scale features within the surface velocity field, thereby providing an overview of the area of interest.

The amount of information gathered regarding the average transport and variability of the Florida Current is impressive, and extremely useful for validating computer models and developing and testing new ideas regarding western boundary currents. Opportunities remain, however, for a higher resolution measurement effort in both vertical and temporal scales within the most dynamic and energetic region on the flow. Through the proper selection and implementation of available and developing current measurement equipment, as well as consideration for lessons from previous studies, these challenges will be met to provide a wide range of researchers, from climate scientists to ocean energy developers, with the information they need to develop new models and systems for the future.

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