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SUBTROPICAL ATLANTIC CLIMATE STUDIES (STACS): WHAT PHYSICAL OCEANOGRAPHERS DO!

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Date: September 19, 2017

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Disclaimer

1. PROLOGUE

We are often asked by friends, “What do you do?” Our quick answer is, “we study the ocean”. Which is exactly what we did, and some of us still do, as physical oceanographers primarily at the Atlantic Oceanographic and Meteorological Laboratory, AOML (oceanographers often use acronyms or initials to eliminate repeated use of long names) of the National Oceanic and Atmospheric Administration, NOAA, and the Cooperative Institute of Marine and Atmospheric Studies, CIMAS, at the Rosenstiel School of Marine and Atmospheric Science, RSMAS, of the University of Miami. Both AOML and RSMAS are located on Virginia Key, Miami, Florida. “Not enough information” is always the reply from our friends, many of whom thought we actually worked for the Central Intelligence Agency since we went to sea for long periods of time in white ships with many large antennas, radars, etc.

Hoping to provide a more satisfactory reply for our friends and any potential future physical oceanographers, perhaps it is useful if a definition of physical oceanography is offered first. NOAA’s National Ocean Service, NOS (oceanservice.noaa.gov), defines physical oceanography as the study of “the physical conditions and physical processes within the ocean such as waves, currents, eddies, gyres and tides.” Physical oceanographers use many tools to study the ocean, from devices making direct observations of a variety of ocean parameters, to satellites that measure the broad oceans from space, to computer “models” that simulate the ocean and help us figure out how the complex systems in the sea work. Thus physical oceanographers have a number of specialties in the field. Herein the focus is on collecting direct observations of the ocean, since that has been our specialty over the years. To illustrate how our research works, the Subtropical Atlantic Climate Studies program (or “STACS”, a title selected to satisfy the requirement for catchy titles for experiments) will provide an example of “What physical oceanographers do”. In what follows, technical terms that might not be known by the reader who is not a specialist are noted in **bold letters** and are defined in the Glossary at the end of this report.

2. STACS/WHAT PHYSICAL OCEANOGRAPHERS DO

Physical oceanographers typically perform the following activities: (1) identify a scientific question that explains how ocean physics plays a role in societal concerns; (2) select measurements that can address the scientific question; (3) obtain funding and establish a management structure; (4) collect the data; (5) analyze the data; (6) publish the results in scientific journals; and (7) develop and implement new strategies to study the new questions uncovered during the study. For each item in that list, examples of some of the important activities conducted by STACS investigators during the experiment in the 1980s are given next (i.e., what physical oceanographers do).

(1) Identify the scientific question: The STACS program was based on scientific questions addressed in earlier experiments, seminars, reports, and **peer reviewed journal** articles. Specifically, earlier work had demonstrated that “The **thermal balance** of the earth is maintained by the transport of heat from the tropics, where incoming solar radiation exceeds outgoing radiation, to middle and high latitudes, where outgoing radiation exceeds incoming radiation”. Scientists had determined that it is the ocean and atmosphere that redistribute that heat in a ‘balance’ that allows the

various parts of the globe to have the various average temperatures that they exhibit. The above quote is from the paper that summarized the rationale for the STACS project in 1983 – researchers identify scientific articles by listing the last name of the author or authors followed by the year that the article was published, in this case as "Molinari (1983)". The complete details of this and all of the other articles cited herein, including the name of the scientific journal where they were published, are presented near the end of this report.

Meridional heat transport by both the atmosphere and ocean is required to maintain the Earth's thermal balance and insure that neither the tropics continuously warm nor the poles continuously cool. Early studies indicated that the atmosphere transported the majority of the heat toward the poles in the middle and high latitudes while the ocean transports more of the poleward heat at tropical and subtropical latitudes (e.g., Bryan et al., 1975; Oort and Vonder Haar, 1976). The North-South transport of heat in the ocean is dominated by a system of ocean flows that circulate all around the globe – physical oceanographers call this system of flows the "Meridional Overturning Circulation", or MOC for short. The portion of the global MOC that is found in the Atlantic Ocean can be simply characterized as the northward flow of warm surface water and southward flow of cold deep water (Fig. 1). Studies of the global climate system have found that **variability** in the intensity of the MOC "would have profound implications for climate change" (Bryden et al., 2005).

In the subtropical Atlantic Ocean near the latitude of Miami, the important components of the MOC are the Florida Current, FC, flowing northward within the Straits of Florida (Fig. 1), and the Deep Western Boundary Current, DWBC, flowing southward east of Abaco Island, the Bahamas (Fig. 1). Around the year 1980 the existence of these flows was well understood; however, there were many uncertainties in the earlier estimates of the strength and variability of these western boundary currents, and about their role in the **oceanic heat flux**. These limits in the existing knowledge motivated further studies to understand in more detail the role of the FC and DWBC on the transport of heat in the North Atlantic. Thus the STACS project was created to identify those processes that contribute most to the transport of heat in the North Atlantic, and to develop the technology to monitor these processes **operationally**.

STACS had an objective, measuring oceanic heat flux in the North Atlantic, and goals, identifying the processes that contribute to this heat flux in the western Atlantic, and developing tools to monitor these processes. The initial location of the study area was selected to be the Straits of Florida at 27°N because of its proximity to Miami, the home of both AOML and RSMAS. This proximity would reduce the ship time required for research ships to reach the study area.

(2) Select measurements: Estimates of the FC component of oceanic heat flux require observations of two quantities: (1) the amount of water being carried by the current, which we call the "volume transport" or sometimes just the "transport"; and (2) the temperature of the water being carried by this flow. The former is the more difficult quantity to measure, so for brevity only the volume transport observations will be discussed in detail herein. After discussion amongst the group of scientists involved, a monitoring strategy to directly measure transport was developed using a

mixture of **direct and indirect measurement methods**. The results from the direct observations, which are typically the most expensive to obtain, would be used to verify and calibrate the indirect observations of transport as summarized in Figure 2. Brief descriptions of some of the measurement systems are given in Appendix 1. The strategy was designed to develop long-term monitoring techniques (the indirect methods) that did not require expensive shipboard measurements (the direct methods).

(3) Obtain funding and develop management structure: NOAA and the Office of Naval Research, ONR, were the science agencies that initially funded STACS. The precise methods for obtaining funding for research differ from one agency to the next (and there have been many changes to these procedures over the years). For the STACS program, NOAA provided support to scientists at AOML after they submitted what were called "program documents" to the appropriate mangers within the agency. ONR provided support to scientists at RSMAS after they submitted what are called "proposals" to the appropriate managers within the Navy.

The documents and proposals that the scientists had prepared demonstrated to the funding managers that these physical oceanographers could successfully achieve the stated goals and objectives of the STACS program. Furthermore, they satisfied the funding agencies that the results of STACS would not only provide useful information to the scientific community but also to the general public (and hence satisfy their constituencies). For instance, the scientific community could build increased understanding of the complicated climate system. The general public would benefit from the resulting scientific knowledge and monitoring tools because of the impacts of these oceanic flows on areas such as commercial and recreational fisheries, shipping and tourism.

An Advisory Council was formed, comprised of STACS investigators (i.e. the physical oceanographers), to provide the management structure for the program. An initial list of **principal investigators** (PIs) comprising the Council and their institutions and measurement focuses are given in Table 1. The PI's were selected for their expertise in the particular measurement systems noted in the Table, which the Council had determined would contribute to the objectives.

(4) Collect the data: Repeated Pegasus profiler stations and fixed current meter moorings were chosen to provide the direct measurements needed (see Appendix 1 for a short description of these measurement systems). The initial cruise to deploy the 5 current meter moorings and to collect the first set of 8 Pegasus stations across the Straits (see Fig. 2; a ninth Pegasus station, termed "station 0", was added later) was conducted in April 1982 using the NOAA Ship *RESEARCHER* (Fig.3), with ship funding support from NOAA. Additional cruises continued through May 1984, recovering and redeploying the moorings when needed and collecting additional Pegasus profiles at the nine stations. These cruises were completed using the University of Miami's ship *R/V CALANUS* and AOML's ship *R/V VIRGINIA KEY* (Fig. 4).

Several indirect observations of FC transport were selected based on results from previous studies. As a first example, as described in Appendix 1, a fluid containing **charged particles** moving through the Earth's magnetic field creates an electric field perpendicular to the motion (Larsen and Sanford, 1985). By installing a voltmeter on an abandoned submarine telephone cable between Jupiter, Florida and Settlement

Point, Grand Bahama Island (Fig. 2), scientists involved in STACS were able to obtain voltage estimates across the flow. These voltages were then calibrated into FC volume transport estimates using the direct observations described previously.

In addition, measurements of sea level differences across the FC (between Florida and the Bahamas) are related to the transport of the current. Differences were calculated from both bottom mounted pressure gauges and coastal tide gauges (i.e., sea level stations) deployed on both sides of the Straits (Fig. 2). The differences were calibrated to provide estimates of the FC transport using the direct observations.

(5) Analyze the data: Scientists need to be very careful when making measurements to ensure that their data are not altered by problems in the way they make their measurements. As an example familiar to the non-specialist, many modern cars measure the outside temperature, but when those cars are first started up after they've been sitting out in the bright sunshine on a hot summer day, the first temperature measurement they provide is usually artificially high because the Sun has been warming the car. The STACS researchers carefully reviewed their measurements to make sure they did not introduce any mistakes into their research due to errors in their measurements. The direct STACS observations were first reviewed to remove erroneous values caused by sensor malfunctions, sensor fouling by flora and fauna in the ocean, and other instrument problems. Analysis techniques included visual inspection of plots of variables versus depth by station (e.g., Pegasus velocity profiles) and time series plots of velocity components measured by the fixed current meters to identify any problem values. This "visual quality control" can be applied onboard the ship as the data are collected or later upon return to the laboratory. For many of the data sets that were collected, more sophisticated computer techniques are applied after the visual quality control to look for non-physical, erroneous data values.

The direct observations obtained at **discrete** points across the Straits (Fig. 2) were used to develop total Straits transport values. For instance, a Pegasus profile provides data observations that are essentially continuous in the vertical direction, but the Pegasus profiles were only calculated at a limited number of locations that were as much as 5 miles apart from each other at discrete horizontal points across the Straits. If the scientists wanted to estimate the total northward transport of the FC, they had to evaluate how quickly the flow changed as one moved across the current. For STACS it was determined that an accurate transport could be calculated by assuming that the velocity observed at a Pegasus station represented a reasonable average over the distance between consecutive stations. Error estimates for the total transport from a Pegasus section were estimated as 1 million cubic meters per second (1 **Sv**) compared to an average of all Pegasus transports of 30 Sv (Molinari et al., 1985).

Both horizontal and vertical estimates of **shear** were necessary to estimate total transport from the discrete current meter data. Comparisons between Pegasus and current meter transports for different deployments were made. These show excellent agreement arguing for consistency in **extrapolation** techniques used for the two data sets (Lee et al., 1985).

Similar techniques to evaluate the accuracy of the indirect observations were applied to those data sets. For example, the voltages observed on the out-of-service telephone cable are affected by signals such as solar storms interacting with the ionosphere at the top of the Earth's atmosphere, and those effects have nothing to do with ocean variations that the STACS researchers wanted to observe (Larsen and Sanford, 1985). These solar-ionospheric signals are removed from the cable time series using careful mathematical techniques (Larsen and Sanford, 1985).

Comparisons between the transports directly measured and calculated by the fixed current meters and by the Pegasus profilers agreed well with each other, suggesting that both direct measurement systems were working well. The direct observations also agreed well with the indirect cable estimates once the latter were calibrated using the Pegasus observations. Thus one of the major results of the STACS program was the confirmation that voltage measurements on the cable could serve as an accurate monitoring tool for the FC transport (Larsen and Sanford, 1985).

The sea level difference observations were also compared to the direct transport estimates, and were calibrated to yield indirect FC transport estimates (Maul et al., 1985). The calibrated sea level data agreed fairly well with the direct observations also, although the differences between the calibrated sea level differences and the direct observations were larger than those for the cable voltage observations. This suggested that the sea level differences could serve as an alternative approach to observing the FC transport indirectly. Because the cable-based estimates were more accurate, it was the cable voltage method that was pursued most consistently after the STACS program ended.

(6) Report results: Scientists present the results of their research in peer-reviewed journal articles, describing in detail the data they collected, the methods of analysis they used, and the conclusions that they draw from their results. The STACS program was so exciting and influential at the time that the results from the first two years of STACS, April 1982 through May 1984, were published as a series of articles in the very prestigious journal *SCIENCE*, as summarized in Molinari et al. (1985). These results were focused on an initial STACS objective of developing tools to monitor operationally the important heat flux processes in the Atlantic Ocean (i.e., the FC). As indicated previously, both the cable voltage based method (Larsen and Sanford, 1985) and sea level difference based method (Maul et al., 1985) were identified as viable indirect (i.e. lower-cost) methods of providing long-term monitoring of FC transport.

Other publications about the STACS results were published in other scientific journals, and they provided descriptions of the variability of the FC and possible mechanisms that might be causing these changes. For example, Schott et al. (1988) found, based on the fixed current meter data, that the FC transport exhibited a **seasonal cycle**. They found significant connections between this cycle and the cycles exhibited by the surface winds at various locations in the North Atlantic. As they noted, these results provided the impetus and direction for additional studies of the causes of the FC seasonal cycle.

(7) Develop and implement new strategies: At most other latitudes apart from 27°N the key flows associated with the MOC are not so conveniently located in a geographically small location close to two oceanographic institutions. For example, western boundary currents at other locations within the subtropical North Atlantic (Fig. 5) could also be useful locations for monitoring the MOC. As the initial stages of the STACS program began to produce results, it was recognized that the MOC

studies would benefit by expanding the observations to a larger region to look at the boundary currents further afield. The role of the currents in these other locations in transporting both warm surface waters from the equator to 27°N and cold subsurface waters from 27°N to the equator was selected as the objective for post-FC STACS.

The first section chosen for these new observations was located east of Abaco Island, the Bahamas, at 26.5°N (Fig. 5). Both the northward flowing Antilles Current transporting warm water, and the southward flowing DWBC transporting cold water, cross this line. Other sections were subsequently established from Abaco southward toward the equator (Fig. 5). Each of these sections was selected to study the western boundary currents of the North Atlantic at that location (Fig. 5) and the processes by which these flows transported heat.

East of Abaco, direct observations of transport and temperature were collected using Pegasus profilers and fixed current meter moorings. Conductivity-Temperature-Depth (CTD)/Rosette data and chlorofluorocarbon (CFC) samples were also taken at stations east of Abaco and on the other sections shown in Figure 5. Current meter moorings and Pegasus profilers were also deployed off Northeast Brazil (Fig. 5).

Details describing the CTD observations are given in Appendix 1. CFCs are a man-made substance (i.e. freons) introduced into the surface of the ocean from the overlying atmosphere. CFCs have no known natural sources. CFC, salinity and oxygen concentrations of subsurface waters are typically imposed on water masses at the sea surface where they are formed. Thus, samples collected from the CTD and Rosette were used to define the source of the waters being carried by the western boundary currents. By tracing these characteristics from one location to another it is also possible to evaluate the continuity of these flows.

The results from analyses of these observations can be divided into the two components of the MOC found along the western boundary. As noted earlier, these MOC components are the southward flow of deeper cold water and the northward flow of warm surface waters. To illustrate some of the scientific outcomes from the STACS program, selected results are briefly presented here.

The DWBC east of Abaco appears as a core of maximum southward flow centered 1500 m below the surface in both current meter and Pegasus data (Lee et al., 1990). A core of high CFC values, indicative of a Labrador Sea source region, is coincident with the velocity core (Fine and Molinari, 1988). The data east of Abaco provide a perfect illustration of a common problem in physical oceanography – the ocean currents don't always appear in the same location over time. East-west motions of the core of the DWBC east of Abaco, for example, caused what appeared to be large transport variations when the flow was measured by shorter sections (current meters or Pegasus profiler sections) that did not resolve the entire southward flow when the strongest flows had moved further offshore (Lee et al., 1990). The total average transport of the DWBC was estimated at 30 Sv. This estimate was approximately a factor of two greater than previous estimates of DWBC transport. This discovery illustrated another challenge that physical oceanographers face – the flows we are studying are not alone in the ocean. The circulation can be complex and it can be hard to trace the flow you're trying to study in and amongst the menagerie of other flows in the region where you are working. In the case of the STACS results, the fact that the DWBC appeared so surprisingly strong was due to the presence of what oceanographers refer to as a "recirculation cell", which is a closed loop of flow that runs parallel to the main current for a while, and then loops back offshore to the opposite direction of the main current, before finally heading back toward the main current and joining it again at some location upstream. The STACS results on the presence of these recirculation cells were critical for establishing future observational efforts to determine the intensity of the DWBC, and hence the MOC.

Fine and Molinari (1988) used CFC and CTD data to show that the core of the DWBC, as identified at Abaco, was found at the sections farther south to 14.5^{o}N (Fig. 5). Molinari et al. (1992) used similar observations to demonstrate that the DWBC extended to the equator. Johns et al. (1993) using current meter data discussed processes that caused variability in DWBC transport close to the equator. Thus, the continuity of the DWBC and the causes of variability in DWBC transport were demonstrated in these data.

With respect to the northward flow of near surface, warm water, Lee et al. (1990), using current meter observations, found a weak Antilles Current (Fig. 5) transport of 3 Sv. Origins of the FC were observed in repeat CTD sections entering the Caribbean through the Antillean Passages (Wilson and Johns, 1997 and Johns et al., 1999) and continuing through the eastern Caribbean (Morrison and Smith, 1990).

Cross equatorial flow of surface waters in the North Brazil Current (NBC, Fig. 5) was not continuous along the western boundary. The NBC retroflects at about 7^{o}N forming eddies containing warm NBC waters (Johns et al., 1990, Fratantoni et al., 1995). These eddies propagate northward along the western boundary. Many of the results described previously appeared in earlier studies. However, STACS further quantified previous results demonstrating the continuity of the northward component of the MOC.

3. LEGACIES OF STACS

Measures of the successes of STACS can be found in activities that began during the program and continue today, as well as in more recent programs that have built upon STACS results to establish their efforts. For example, as discussed earlier, an abandoned submarine telephone cable was calibrated during STACS to obtain daily estimates of FC transport. When that cable was broken due to damage from a ship anchor, Larsen (1991) found that a calibrated in-service submarine telephone cable, located south of the cable used during the initial phase of STACS, would provide similar transport accuracies. And when that second cable ceased being used for telephone transmission, permission was sought and granted to collect data on the now out-of-use cable into the future, a system that is still in use today. Daily in-service and abandoned calibrated FC transport values are available from 1982 to the present on www.aoml.noaa.gov; this 30+ year nearly continuous daily record of transport is unprecedented, and is the longest time series of transport estimates from a major ocean current in existence. Meinen et al. (2010) used a portion of this record to study long-term variability of the FC and possible forcing mechanisms for these features. Innovative young researchers have also used these data to develop new estimates and analyses; for example, Shoosmith et al. (2008) used STACS Pegasus data to calibrate the cable data to give temperature transport.

F. Schott was an original STACS investigator (Table 1) who worked at RSMAS until the late-1980s. Upon leaving RSMAS he returned to his native Germany where he worked at the Institute fur Meereskunde in Kiel Germany. Even though he had left Miami, he continued to apply the lessons learned from STACS as he began a study of the DWBC at 8°S. Using current meter moorings that were in the ocean from 2000 through 2003, Fritz and his colleagues studied the DWBC far downstream from Abaco Island (Dengler et al. 2004). They found that the DWBC was indeed continuous along the western boundary from the equator (i.e., which was as far south as the STACS observations described earlier had made it) to 8°S along the western boundary. They also used results from an ocean numerical model to show that the DWBC could break up into migrating eddies at this latitude as it continued southward.

The continuing FC cable measurements became, in the year 2000, part of a new study called the NOAA Western Boundary Time Series (WBTS) project. In 2004, the WBTS project restarted the STACS-era DWBC observing program utilizing the same fixed mooring sites that had been used in the late 1980s and early 1990s but new acoustic-based technologies. And these WBTS successors to STACS provided the cornerstones for the RAPID-MOCHA-WBTS, RMW program (www.rapid.ac.uk/rapidmoc/). RMW was designed to obtain time series observations of the MOC and total oceanic heat flux through a trans-Atlantic array spanning from Florida to Africa at approximately 26.5°N. Just as during the STACS era, the modern cable observations provide a continuous measure of the FC warm-water component of the MOC. And just as during STACS, observations from moored instruments east of Abaco provide a measure of the DWBC cold-water transport of the MOC.

Scientists from Great Britain (the National Oceanography Centre Southampton) and the USA (RSMAS and AOML) lead the RMW array. Fieldwork for the array began in 2004 and continues today. Observations are taken along the entire trans-Atlantic section at 26.5°N to define the properties of the MOC and oceanic heat flux at this latitude. McCarthy et al. (2015) and Frajka-Williams et al. (2016) provide some of the recent RMW results.

Lessons learned from STACS, along with results since then, have also led to a similar effort to measure the MOC in the South Atlantic – termed the South Atlantic MOC (SAMOC) program (www.aoml.noaa.gov/phod/SAMOC_international/index.php). The international scientific partners leading SAMOC have deployed an array across 34.5°S, similar to the RMW array at 26.5°N, to study the MOC and how it varies in the southern hemisphere. The SAMOC partners include scientists from the United States (AOML), Argentina, Brazil, France and South Africa. Meinen et al. (2013) provide early results.

4. EPILOGUE

As stated in the *PROLOGUE*, "What physical oceanographers do" has been an effort to explain to non-specialists how these scientists study the ocean and how their lessons learned can affect what comes afterward. This has been illustrated using the activities of the STACS program that began in 1982. Seven types of STACS activities were initially given and discussed, each providing examples of how physical oceanographers do their work. STACS goals were directed at the program's objectives of identifying the processes, which contributed to oceanic heat flux and developing tools to monitor these processes.

Oceanic heat flux was addressed using the context of the MOC, which is characterized as the northward flow of warm surface waters and the compensating southward flow of cold deep waters. The mechanisms for the warm surface flow were studied along the western boundary. The FC was initially considered, followed by upper layer features along this boundary, extending southward along the boundary. The scientists working on STACS found that the structure of the warm flow was complicated, composed of cross-equatorial flow, separated rings, and flow into and across the Caribbean. The DWBC was shown both to be an important component of the cold southward flow and continuous from 26.5^{o}N to at least the equator.

The scientists involved in STACS utilized many different types of measurement systems in their studies (see also Appendix 1). Abandoned and active submarine telephone communications cables provided an operational system to monitor the FC transport. Sampling requirements for observing the DWBC were determined from analysis of current meter moorings to provide the methods needed for future programs. Thus in summary, STACS met its initial objectives of identifying mechanisms of oceanic heat flux and also providing monitoring tools and methods for the future. The many legacies to the STACS program continue these types of study.

Finally, as noted earlier, documents and proposals written to obtain funding for STACS included statements that illustrated how the goals and objectives of the program would provide information and services not only to the scientific community but also to the general public (who ultimately provide the funds needed for all of this work). The many legacies of STACS provide examples of how the program provided information to the scientific community (e.g., input for climate and ocean monitoring projects such as WBTS). And as for payoff to the public who funds this work, examples of how the program was useful include the development of High Frequency Radar (HFRADAR) that is used to map coastal surface currents and define the axis of the FC. This has proven useful to scientists, who have noted that the position of the FC axis east-west within the Straits does not have a major effect on the FC transport (Schott et. al., 1986). And for the public, HFRADAR was shown to be an effective measure of coastal flow (e.g., Schott et al., 1985), thereby providing important information for coastal communities (e.g., fisheries, tourism, navigation, etc.). An array of HFRADAR was deployed along the east and west coast of the United States (cordc.ucusd.edu/projects/mapping/maps). This array continues to provide surface current maps to the general public. So, clearly the ultimate goal of STACS has been met, in that the science learned in the program has benefitted not only the march of scientific progress but also the general public that provided the research funds.

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6. *APPENDIX*: A brief description of the observation systems used in STACS.

Pegasus stations: Pegasus is the name given to an **autonomous** velocity and temperature **profiler**. Pegasus was developed by Dr. T. Rossby, a professor at the University of Rhode Island, for use in another western boundary current, the Somali Current of the western Indian Ocean. A Pegasus unit internally records pressure, which tells the scientist how deep the instrument is, and the time when sound signals arrived from two previously deployed bottom-mounted beacons. The difference between the time when the beacon emitted the sound and when the Pegasus profiler heard it can be used to estimate the distance between the beacon and the profiler because scientist have good observations of how quickly sound moves through the water. With the two distances from the two different beacons, together with the depth information from the pressure measurement, scientists can determine the precise location of the profiler. By looking at the differences in position from one set of measurements to the next, scientists can estimate the velocity of the water as it pushes the profiler horizontally while it falls through the water. Figure A1 demonstrates the Pegasus operation. The estimates of horizontal velocity obtained from the Pegasus measurements are accurate to within about 1 cm/s.

Nine pairs of acoustic beacons were deployed near 27^{o}N across the Straits for use in the Pegasus observations – these beacons were used to collect velocity profiles at nine stations spanning the Straits (Fig. 1). Collecting data at these nine stations during a single cruise constituted what oceanographers refer to as a "section"; occupation of an entire section took about 16 hours. During the initial STACS period, April 1982 to May 1984, the section was occupied roughly 100 times.

Current meter moorings: Five locations were selected for continuous observations of the FC flow during the STACS program. These "current meter mooring stations" were established across the Straits of Florida at the locations shown in Figure 1. At each station, one or more current meters were attached at various depths to a strong line (Fig. A2). The line is moored (anchored) on the ocean floor with a heavy weight (e.g. old railroad wheels) and is held nearly vertical by attaching one or more buoyant floats to the upper end of the line.

During STACS, the current meters used were rotary types. This type of current meter uses a rotor that is spun by the water as it pushes past the instrument. By counting the rotations of the rotor, the instrument gives a measurement of how fast the water is moving. The rotary type current meter determines the direction of the flow by using a large vane connected to the body of the instrument. A compass in the current meter determines the orientation of the vane, and thus provides the flow direction. Both speed and direction were recorded internally in the meter every hour.

Batteries within the instrument housing powered the measurement and data recording systems. During STACS, based on battery lifetimes, moorings would be deployed for up to a year. Intense shipboard operations were required to deploy and retrieve these moorings. The data resulting from the deployments are analyzed at the laboratory.

Conductivity Temperature Depth (CTD) sensors/Rosette samplers: A CTD/Rosette unit is deployed from a research vessel as shown in Figure A3. The unit is attached to a winch by an electrical cable and is lowered down toward the bottom of the ocean slowly while it makes its measurements. The CTD includes sensors that measure pressure (which tells us the depth), temperature, conductivity (which is a measure of how much salt is in the water, i.e. the salinity) and oxygen (which tell us how much dissolved oxygen is carried in the water). The data from these sensors is transmitted up to a surface recording unit via the electrical cable.

The Rosette sampler is attached to the CTD unit. Sampling bottles are attached to the Rosette sampler and are submerged with the CTD. The bottles are sent down open, and because of the intense high pressures in the ocean the bottles are only closed while the unit is being brought back up to the surface. When the unit reaches a prescribed depth, salinity or oxygen value the operator sends a signal to the Rosette closing the bottle. The signal from the operator closes the bottles at the desired depths collecting a sample of the water at that depth; this sample can subsequently be analyzed on the ship or back at the lab to determine the quantities of important water properties such as salinity, dissolved oxygen and chlorofluorocarbon (CFC) content.

The salinity and oxygen values are used to calibrate the CTD sensors either during the cruise or later at the laboratory. No electronic sensor existed during STACS (and still not today) to measure CFCs, so the water samples that are collected by the sample bottles are the sole source of observations of this important quantity. The CFC data are invaluable for identifying the source regions where water masses developed their characteristics.

Cable voltages used to estimate volume transport: The main **indirect** method used in the STACS program was based on voltage measurements on an out-of-service telephone cable that stretched along the bottom of the sea from Florida to Grand Bahama Island. This truly unique system takes advantage of a simple physical fact – if you move a **charged particle** through a magnetic field, you will create an electrical field that is perpendicular to the direction you are moving the particle. The details of how this works are a bit complex and have been described elsewhere (e.g. Larsen and Sanford, 1985); in brief, because the salt particles in the ocean carry a small electrical charge, as they move northward in the FC through the magnetic field maintained by the Earth, they create a very weak electric field across the Straits of Florida. By measuring the very small voltage this electric field creates on the out-of-service telephone cable (roughly 1.5 volts), we can make an estimate of the FC volume transport. The relationship between the voltages and the transports was determined by using the **direct** measurements from the Pegasus profilers.

7. TABLE: List of the initial STACS **principal investigators** (and members of the STACS Advisory Council) and the instruments they focused on with their research. Affiliation abbreviations: NOAA, National and Atmospheric Administration; AOML, Atlantic and Meteorological Laboratory; RSMAS, Rosenstiel School of Marine and Atmospheric Science; IOS, Institute of Ocean Sciences, Canada; WPL, NOAA's Wave Propagation Laboratory; PMEL, Pacific Marine and Environmental Laboratory; APL, Applied Physics Laboratory, University of Washington.

Investigator	Institution	Focus
H. DeFerrari	RSMAS	Acoustic systems
D. Farmer	IOS	Acoustic profiling
S. Frisch	WPL	Surface radar
J. Larsen	PMEL	Submarine cable
K. Leaman	RSMAS	Current profiling
T. Lee	RSMAS	Current meters
G. Maul	AOML	Coastal tide gauges
R. Molinari	AOML	Current profiling
F. Chew	AOML	Bottom pressure gauges
T. Sanford	APL	Electromagnetic systems
F. Schott	RSMAS	Current meters

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9. GLOSSARY

Autonomous: In the context of an oceanographic measurement device, this term is used to refer to devices that are not attached to a research vessel or to the sea floor.

Charged particle: A particle of material that carries an electrical charge, such as a salt particle dissolved in water.

Direct and indirect measurement methods: Scientists can observe the quantities they need to measure either directly or indirectly. As an example of the difference, consider measuring the temperature of the water in a pan that is being heated. A 'direct' measurement would be made by putting a thermometer into the water to see the temperature. An 'indirect' measurement would be watching to see when the water began boiling, at which point you would know the water was 212°F (100°C).

Discrete: An isolated point in space.

Extrapolation: Estimating a property by assuming observed trends continue as measured.

Meridional: The North-South axis of direction.

Oceanic heat flux: The transport of heat by the ocean typically given through a latitude section extending across an ocean basin.

Operationally: Operational observations are those collected routinely, satisfying a specific objective and maintained long-term (e.g., weather observations).

Peer reviewed journal: Manuscripts are submitted to these journals for anonymous reviews (i.e., peers of the author). The journal requests responses to the reviewer's comments from the author(s). The article is published if the editor accepts the responses.

Principal investigator: A scientist who is one of the leaders of the research involved in a research project.

Profiler: A device that moves vertically through the ocean making measurements at each depth as it passes by. The term is usually used for instruments that are **autonomous**.

Seasonal cycle: Temporal change of a property with the season.

Shear: Change in velocity with distance.

Sv: Shorthand for Sverdrup (a famous oceanographer), a *Sv* is a mass transport unit. 1 Sv = 1×10^6 m^3/s. For reference, the discharge of the Mississippi River is 0.6 Sv.

Thermal balance: Physical oceanographers can carefully calculate a ‘budget’ of heat in the same way that one would maintain the family budget – i.e. measuring how much money (or heat) comes into the home (or the ocean) from different sources (salary, lottery winnings, etc.), how much goes out of the home to different expenses (rent, car payments, etc.), and how much the money in hand changes in value due to inflation. The phrase “thermal balance” means that the oceanographer has an understanding of how much heat is coming into one part of the ocean, how much is leaving that part of the ocean, and how much the temperature of that part of the ocean is changing over time.

Variability: Change of a property with either time or space.

10. FIGURES

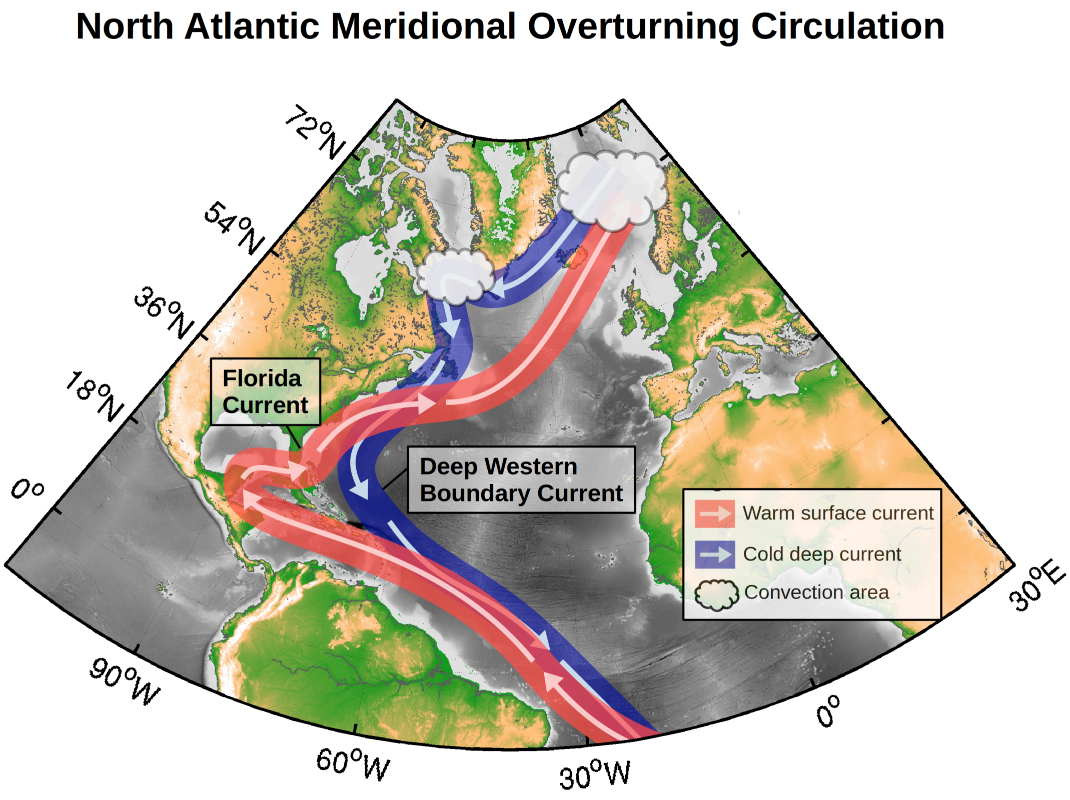

Figure 1: Schematic representation of the North Atlantic Meridional Overturning Circulation characterized by northward flow of warm surface waters (red line), sinking at poleward latitudes (white area) and southward flow of cold deep waters (blue line). Adapted from UK Department of Environment, Food and Rural Affairs, Met Office Hadley Centre, Climate change and the greenhouse effect: a briefing from the Hadley Centre, December 2005, p. 58.

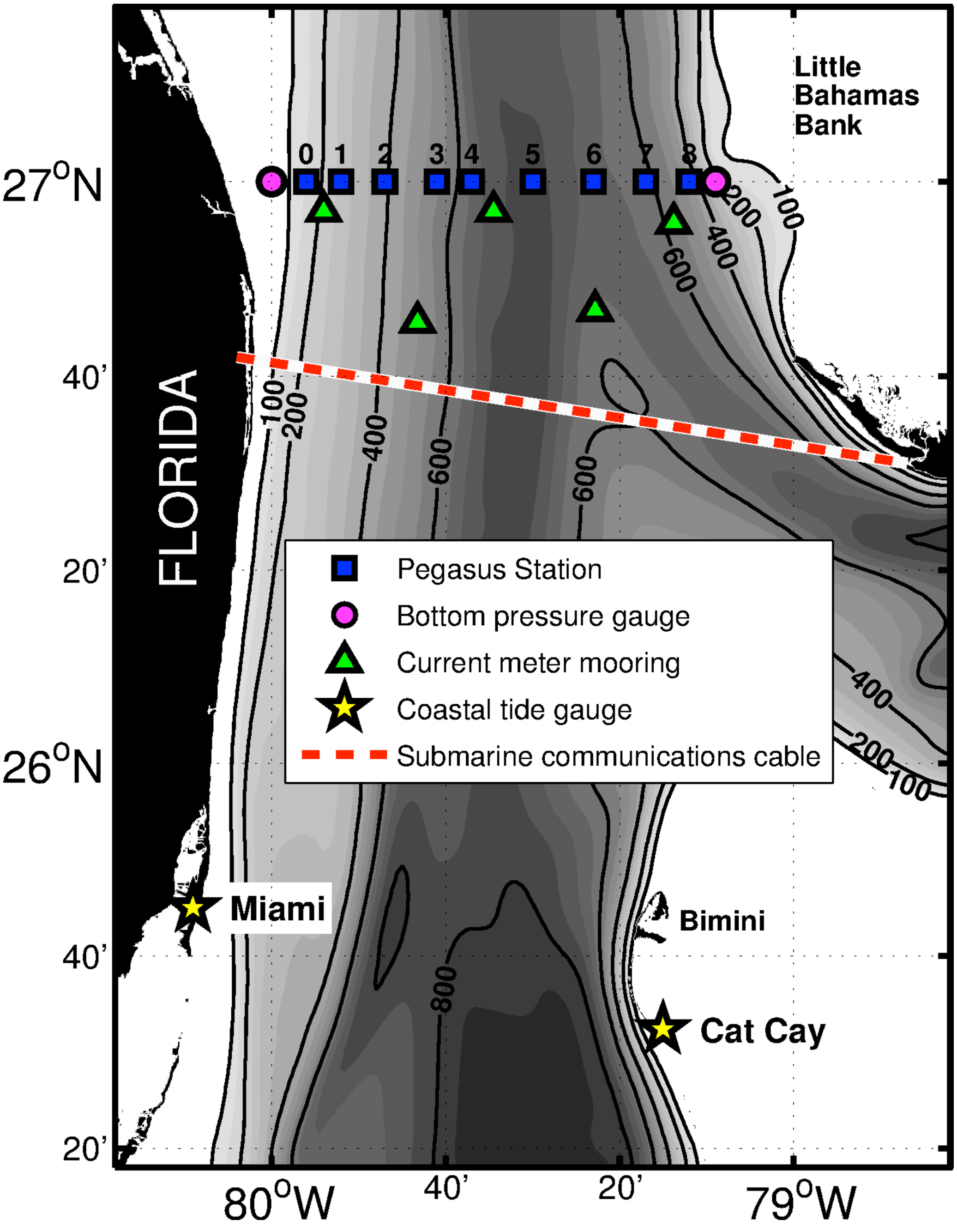

Figure 2. Distribution of sampling strategies in the Straits of Florida. Inset shows how the direct observations were used as standard to verify/calibrate the indirect techniques. Adapted from Molinari (1983).

Figure 3. NOAA Ship *RESEARCHER* (R103) was a 278.3’ research vessel commissioned in 1970 and decommissioned in 1996.

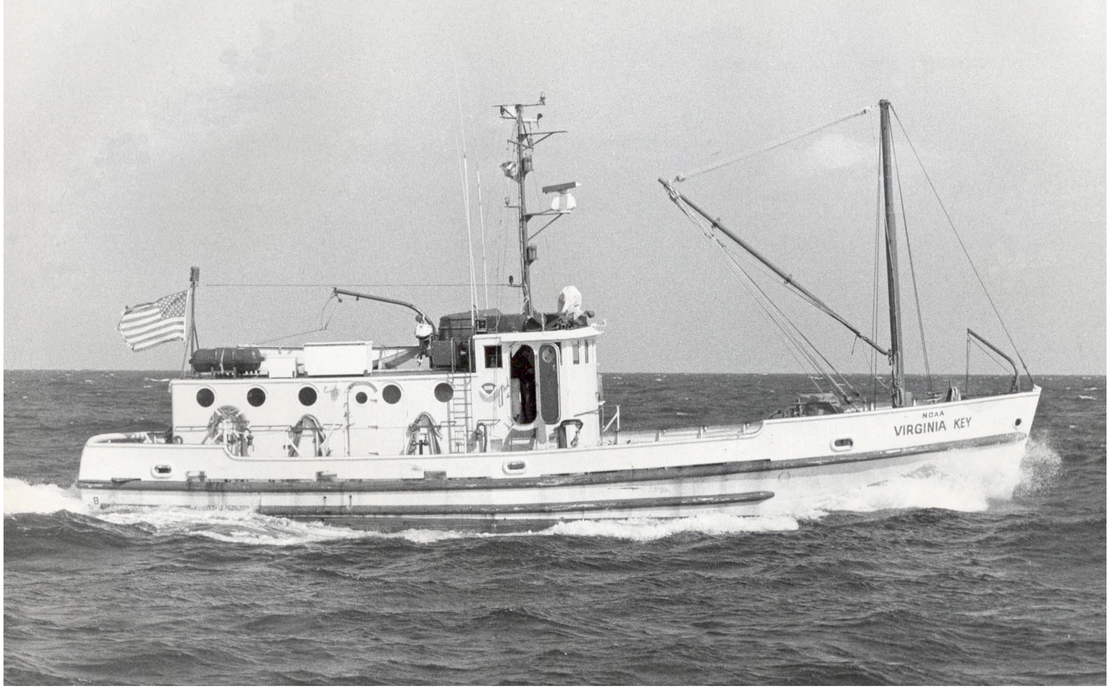

Figure 4. *RV Virginia Key* a 65’ research vessel operated by NOAA’s Atlantic Oceanographic and Meteorological Laboratory.

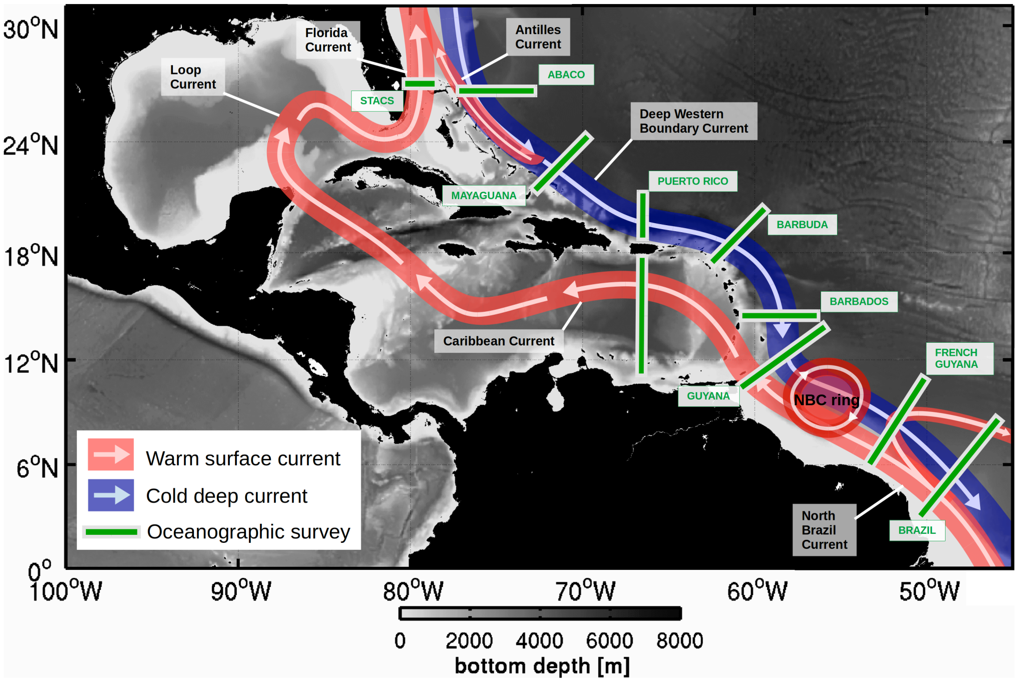

Figure 5. STACS CTD and current profiler sections along the western boundary of the tropical and subtropical North Atlantic Ocean with section names given. Solid red lines represent the warm water component of the MOC (Fig. 1) and dashed blue lines represent the cold water component of the MOC. Abbreviations are given for currents; DWBC = Deep Western Boundary Current, FC = Florida Current, AC = Antilles Current, CC = Caribbean Current, NBC = North Brazil Current and circulation features, Ring = eddies separated from NBC.

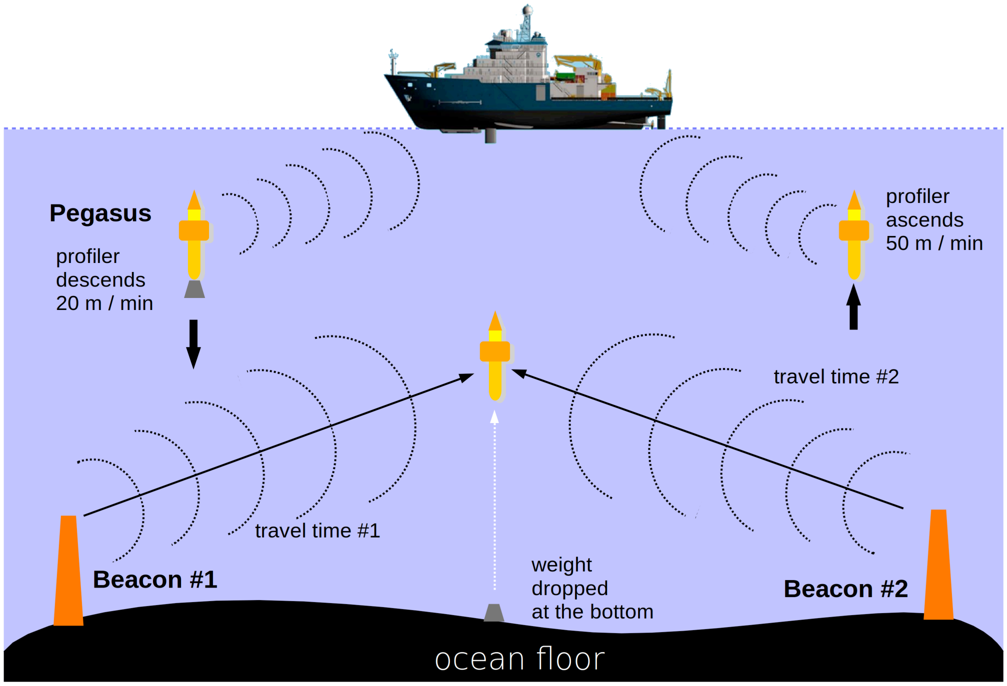

Figure A1. The Pegasus profiling system. Pegasus is acoustically tracked relative to two beacons deployed on the bottom. Transmissions from the unit enable its movement to be monitored from the ship. Every 8 s, the pressure, temperature and travel times from the two beacons are logged in Pegasus. Adapted from Spain et al., 1981.

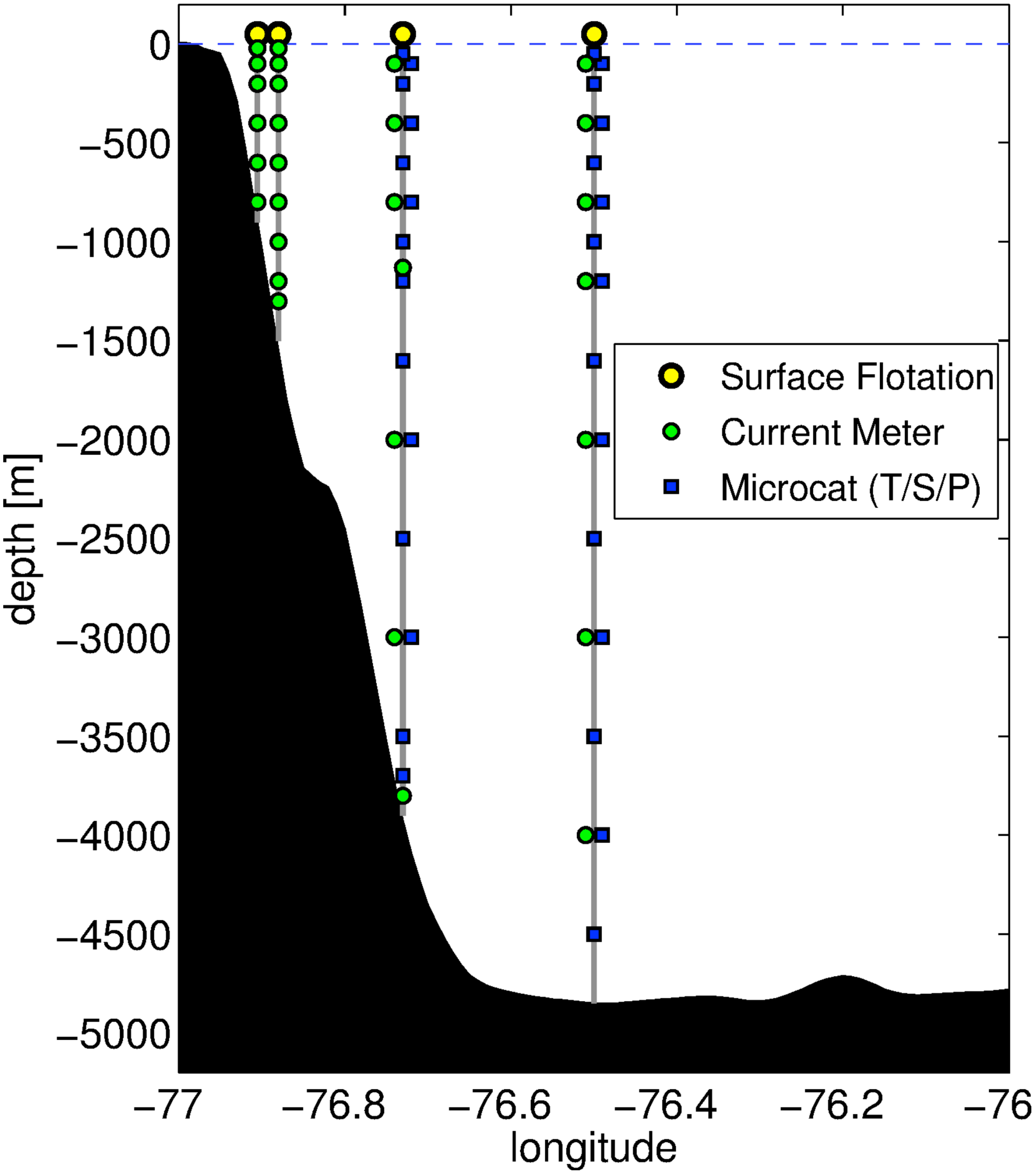

Figure A2. Cross-sectional view of a portion of the western boundary array over topography showing the instrument types and depths on the moorings. Adapted from www.rsmas.miami.edu/users/mocha/mocha-methods.htm.

Figure A3. AOML scientists collecting water samples from the CTD/Rosette package.


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