Reports

Subtropical Atlantic Climate Studies: Introduction

Abstract. *This report is an introduction to the accompanying collection of reports that present the results of a 2-year period of intensive monitoring of the Florida Current. Both direct observing systems (ship-deployed current profilers and moored current meters) and indirect observing systems (coastal tide gauge stations, bottom pressure gauge arrays, a submarine cable, acoustic arrays, and radar installations) were used to measure temperature and volume transport.*

Recent climate studies have demonstrated that the ocean exerts an effect beyond the passive and local role in global energetics of storing heat in the summer and releasing heat in the winter. The combination of meridional oceanic heat flux and atmospheric energy fluxes serves to maintain the global thermal equilibrium by moving heat from tropical regions, where there is a net radiation gain at the top of the atmosphere, to polar regions, where there is a net radiation deficit (*1–3*). It is expected that in the future researchers will be able to quantify the impact of this redistribution of heat on the mean and time-dependent global climate, using data derived from general circulation models (GCM's) of the coupled ocean-atmosphere system that are now being developed. However, even at this stage of the evolution of GCM's, it is clear that advection of heat by ocean currents plays a major role in determining climate. For example, in a simplified GCM with idealized geography, ocean circulation is responsible for increased surface temperature at high latitudes, reduced snow and sea-ice coverage, and reduced sensitivity of the model climate to changes in the atmospheric carbon dioxide concentration (*4*). The global distribution of meridional ocean heat flux and the internal oceanic processes that contribute to this flux are at present poorly known. The Subtropical Atlantic Climate Studies (STACS) program was conceived to increase our understanding of oceanic circulation and its role in establishing global climate.

Furthermore, long time series of oceanographic data from critically placed monitoring arrays are presently required to provide constraints on results from developing GCM's. In the future, these data will be required as input to verified GCM's when run in the prognostic mode. Thus, additional objectives of STACS are (i) to develop the technology to monitor climatically important oceanic processes and (ii) to begin monitoring operations for long-term climate studies.

The North Atlantic Ocean was selected for the focus of STACS because recent research has indicated a larger poleward heat flux in this basin than in the North Pacific Ocean (*3, 5*). In addition, the largest signal in oceanic heat flux apparently occurs across the latitude band 20°N to 30°N (*3, 6*)—that is, the region of the subtropical gyre in the North Atlantic. STACS objectives were therefore further focused on those components of the circulation of the subtropical gyre at about 25°N that may contribute to meridional heat flux.

Oceanic heat transport through a section of zero net transport is effected by the covariance of temperature and velocity. Ideally, detailed sections of temperature and normal velocity across a basin would be available to estimate the average heat transport over some time period. However, such data are not available. Historically, investigators have therefore decomposed the total flow field into components, which, through various simplifications, could be evaluated from available data. For each component, the transport of the northward flow and the compensating southward flow must be equal (*7*). The net heat flux is then given by the difference in temperature between the two flows multiplied by the transport.

Total flow through a mid-latitude section can be decomposed into a depth-averaged (barotropic) mode and a depth-dependent (baroclinic) mode (*8, 9*). Temperature can be decomposed similarly. The barotropic mode has been related to the horizontal circulation in the subtropical gyre and the baroclinic mode to the vertical (overturning) circulation. The baroclinic mode can be further decomposed into geostrophic and Ekman modes (*8, 9*). Although this decomposition of total flow fields is somewhat arbitrary, it has the advantage of focusing attention on the dynamics of heat flux rather than merely on the magnitude of this flux. Thus, we will also increase our understanding of the North Atlantic circulation by addressing such questions as the relative importance in establishing gyre strength of wind forcing of the horizontal circulation versus thermal forcing

Table 1. Completed and planned STACS observations (see Fig. 1).

Observing system	1982									1983												1984					
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Current meter array	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→
Profiling cruises	X		X			X		X			X		X	X		X	X		X		X	X		X		X	
Submarine cable	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→
Coastal tide gauges																											
Miami	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→
Cat Cay	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→
Pressure gauges																											
A	—	—	—	—	—	—	—	—	—	—	—			—	—	—	—	—	—	—	—	—	—	—	—	—	→
B		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→
C																					—	—	—	—	—	—	→
Surface radar			X													X	X				X	X					
Acoustic array															X	X			X	X	X						

of the vertical circulation. It may also be possible to tailor a monitoring strategy by using indirect techniques to examine a particular process; this would reduce the need for labor- and resource-intensive direct methods.

Initially, STACS activities were focused on studying the Florida Current and its role in heat flux because earlier studies have shown that this western boundary current is a major factor for heat flux across 25°N (*8–12*). The initial objectives are to develop the capability to monitor the annual cycle and interannual variability of the volume and temperature transport of the Florida Current and to understand the relation of the Current's variability to regional and basinwide circulation patterns (that is, Is the Florida Current volume transport an important "index" for basinwide air-sea interaction?). Once coupled GCM's have been adequately verified, sensitivity studies can be performed to determine quantitative sampling requirements for a Florida Current monitoring scheme. At present, however, sampling requirements must be estimated empirically. We use arguments similar to those given by Bretherton *et al.* (*13*) to specify tolerances for the STACS Florida Current transport and temperature observations.

A summary of mean annual oceanic heat flux estimates across 25°N has been reported by Hastenrath (*14*). The mean and standard deviation of seven different flux estimates derived from two independent approaches is 1.20 ($\pm$ 0.17) $\times 10^{15}$ W. Although the small standard deviation suggests a fairly accurate estimate for heat flux, both Wunsch (*10*) and Hastenrath (*14*) have noted that the error bars for the individual estimates are quite large. In fact, several of the estimates of northward heat flux are not statistically different from a zero net flux across 25°N. With these caveats in mind, we assume that for these qualitative arguments net flux can be considered in terms of only the depth-averaged mode; that is, net heat flux is given by the product of Florida Current transport and the difference in average temperature between the northward-flowing Florida Current and the midbasin return flow. The mean annual transport of the Florida Current is 30 $\times 10^6$ m^3/sec (*15*), which for a heat flux of 1.2 $\times 10^{15}$ W implies a temperature difference of 10°C. If we somewhat arbitrarily require a 10 percent accuracy in our flux estimates and assume, as Bretherton *et al.* (*13*) did, that temperature estimates are relatively error-free, then we must resolve the mean annual Florida Current transport to 3 $\times 10^6$ m^3/sec. If, however, we are interested in resolving the annual signal, accuracies of better than 0.5 $\times 10^6$ m^3/sec are required.

To meet the initial objectives of STACS of developing a Florida Current monitoring scheme in the Straits of Florida, a 2-year intensive observing period was initiated in April 1982. Both direct and indirect observing systems were deployed to determine which system or mix of systems will provide the most accurate and efficient monitoring array. The location of all the systems is shown in Fig. 1.

Direct observations of Florida Current temperature and volume transport were provided by ship-deployed current profilers and moored current meter arrays. Profilers provide fine resolution of temperature and horizontal velocity components in the vertical but coarse resolution in time and horizontal space. These measurements represent the primary standard against which other systems are verified and calibrated. Data from current meters are frequent in time but sparse in the vertical and horizontal. In particular, because of technical limitations, current meters cannot be placed near the surface in the Florida Current. Thus, an algorithm is required to obtain total water column transport from these

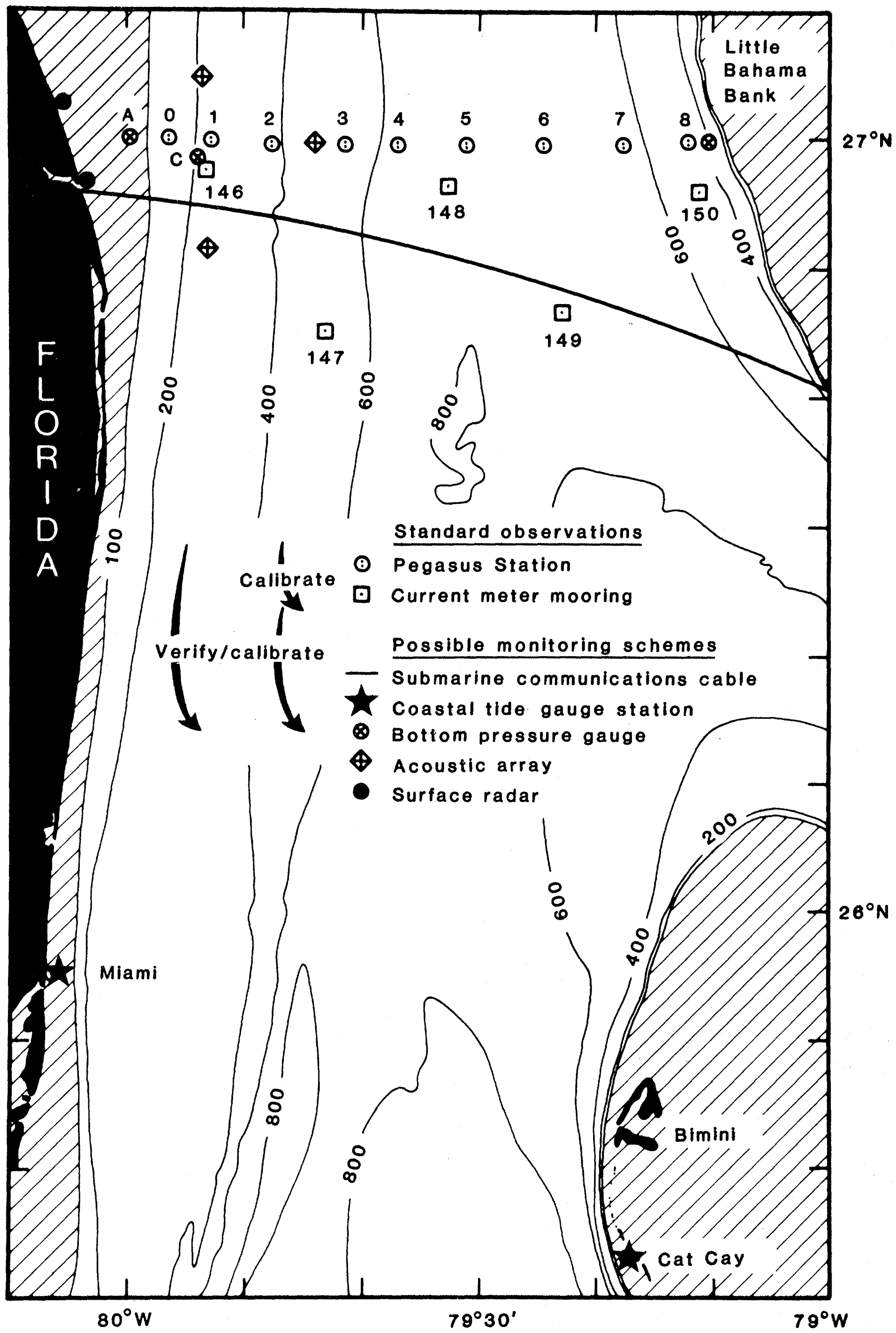

Fig. 1. Distribution of sampling strategies in the Straits of Florida. The inset shows how the direct observations were used as standards to verify and calibrate the indirect techniques.

Table 2. STACS principal investigators. Abbreviations: NOAA, National Oceanic and Atmospheric Administration; AOML, Atlantic Oceanographic and Meteorological Laboratory; RSMAS, Rosenstiel School of Marine and Atmospheric Science, University of Miami; IOS, Institute of Ocean Sciences, Sidney, British Columbia, Canada; WPL, Wave Propagation Laboratory; PMEL, Pacific Marine Environmental Laboratory; APL, Applied Physics Laboratory; University of Washington.

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

data. However, once an algorithm is developed, the current meter data can provide a valuable secondary standard for verifying and calibrating the indirect techniques.

The indirect systems include coastal tide gauge stations, bottom pressure gauge arrays, a submarine cable that measures potential differences across the Straits of Florida, acoustic arrays that measure travel times between sources and receivers, and radar installations that measure surface currents. The utility of these systems is a function of how well the observed variable tracks either mass or temperature transport as determined by comparison with the direct observations. A summary of the approach applied in the Straits of Florida is shown in Fig. 1. Table 1 is a time-line chart of the measurements taken thus far. The intensive observing period was designed to obtain sufficient data to ensure that the indirect systems adequately resolve the relevant scales of motion present in the straits (*15–18*) and to determine which of the direct observations would be most effective for a long-term monitoring effort.

Concurrently, efforts are under way to develop the technologies necessary for determining and, at a later stage, monitoring heat flux processes in the midbasin. Much of this work is devoted to developing systems suitable for placement on ships of opportunity, both research and merchant vessels. Table 2 lists all the STACS principal investigators and their areas of interest.

The series of reports that follows presents the results from an analysis of the data collected during a portion of the intensive observing period (April 1982 through August 1983). In particular, the profiler, current meter, submarine cable, and tide gauge data are considered with emphasis on the volum transport observations. The temperature observations and other systems, such as the acoustic array and radar installations, will be described in future papers.

The results presented in this set of reports show for the first time that submarine cable, coastal tide gauge, and bottom pressure gauge data can provide calibrated and continuous observations of Florida Current volume transport. Although there are differences between the comparisons of cable transport data and profiler transport data in these reports (attributable to somewhat different interpolation techniques used on the profiler data), the comparisons show that we are close to achieving the error tolerances described above with either cable or bottom pressure gauge observations. The tide gauge data are somewhat less accurate. STACS estimates of Florida Current heat flux, computed from historical data for the temperature of the return flow, are consistent with earlier estimates of this flux (*9*). The relation of Florida Current transport variability to local, regional, and basinwide wind forcing is considered.

These results encourage us to continue STACS studies. Because the cable measures volume transport with an apparent error of less than 1×10^6 m^3/sec, the cable will provide the foundation for an ongoing monitoring effort. Coastal tide gauge data obtained as part of the national tide gauge network will also be analyzed as part of a transport monitoring effort to provide an independent and more robust backup data source. Consequently, the direct observations can now be phased out, freeing resources for studies of other heat flux processes. One such process to be studied during 1985 is the effect of currents along topographic features such as the Bahamian continental slope and the Mid-Atlantic Ridge on the magnitude of poleward heat flux. Bryden and Hall (*9*) have estimated that this component of heat flux is 7 percent of the total flux across 25°N. However, the data sets used for these computations are very sparse and errors can be quite large. The multiobserving system approach adopted to study the Florida Current (profiler stations, bottom pressure gauges, and current meter moorings) will also be used to observe the flow east of the Bahamas at approximately 27°N; a 2-year intensive observing period is envisioned.

We expect that analysis of the data collected during STACS will continue in an effort to describe the major scales of motion in the Straits of Florida and to relate the variability to possible forcing mechanisms. Numerical modeling as well as empirical studies are under way. An approximately 5-year time series of cable data exists (*19*). In addition, coastal tide gauge data collected as part of the national tide-gauge network provide a longer time series of transport (*20*). Both data sets provide invaluable time series with which to compare numerical model results.

ROBERT L. MOLINARI
GEORGE A. MAUL
FRANK CHEW
WILLIAM D. WILSON
MARK BUSHNELL
DENNIS MAYER
National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida 33149
KEVIN LEAMAN
FRIEDRICH SCHOTT
TOM LEE
RAINER ZANTOPP
University of Miami, Miami, Florida 33149
JIMMY C. LARSEN
National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, Seattle, Washington 98115
THOMAS B. SANFORD
University of Washington, Seattle 98105

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Volume and Heat Transports of the Florida Current: April 1982 Through August 1983

Abstract. *Absolute velocity and temperature profiles are used to estimate the volume transport through the Straits of Florida and, in combination with historical midbasin data, to estimate the total meridional heat flux through a section at 27°N. The mean annual volume transport of the Florida Current from April 1982 through August 1983 is 30.5 (± 1) × 10^6 cubic meters per second. The net northward heat flux through the 27°N section is 1.2 (± 0.1) × 10^{15} watts. The volume transport is characterized by high values in the late spring and early summer and low values in the late fall and early winter. There is a similar cycle in total heat flux.*

Vertical profiles of horizontal velocity components and temperature obtained during the Subtropical Atlantic Climate Studies (STACS) from April 1982 through August 1983 are used to estimate the mean annual and seasonal cycle of the volume and temperature transports of the Florida Current. Although similar profiler data have been obtained in the past (*1–3*), these historical data were collected intermittently during different seasons over many years. The STACS data were collected at approximately 2-month intervals from April 1982 through August 1983. The mean annual heat and volume transports as measured during STACS are similar to the historical data; a seasonal signal in heat transport is also exhibited.

The data were collected with a current profiler called Pegasus (*4*). A series of nine Pegasus stations is maintained across the Straits of Florida at 27°N (*5*). The Pegasus cruises were designed (i) to observe the annual cycle in volume and heat transport, (ii) to resolve important scales of motion with periods between 2 days and 2 weeks, and (iii) to provide calibration data for the remote-sensing techniques being tested concurrently as monitoring tools (*5*). Pegasus operations provide continuous data in the vertical at relatively closely spaced stations (~10-km separation), but the data are obtained only during relatively short (~2 week) cruises.

Data from nine cruises have been analyzed for use in this report. Two ships were used during the April, June, and September 1982 cruises and one ship during the November 1982 and February, April, May, July, and August 1983 cruises. Cruise length varied because of ship availability, weather conditions, and instrument problems. The typical cruise length was 8 to 14 days. Various sampling strategies were tested, but during a typical cruise continuous west-to-east station occupation was followed by east-to-west station occupation. This procedure resulted in unequal time intervals between occupation of the same station. A complete crossing of the section typically required 16 hours.

The raw Pegasus data were edited and interpolated to 10-m values (*6, 7*). Depth-averaged values of temperature and the velocity components were computed for each station. Daily values of depth-averaged temperature and the north component of velocity were obtained by means of an interpolation scheme in time which also smoothed the raw time series. Missing daily values were filled in with the use of linear regression relations with adjacent stations.

Sampling and instrument errors are present in the various transport estimates. The Pegasus internally records temperature, pressure, and travel times to two bottom-mounted transducers. If the geometry of the transducers relative to geographical coordinates is known, the trajectory of the Pegasus can be computed as it sinks and rises through the water column. Horizontal velocity components can then be determined. Inaccurate positioning of the transducers or poor positioning of the Pegasus relative to the transducers when launched can cause errors in the velocity components (*4, 6*).

Velocities can be computed from data collected during both the up- and the downcasts. Differences between up- and downcast north component of speed and temperature (Table 1) provide a measure of the repeatability of the Pegasus observation. The largest differences and standard deviations in speed and temperature typically occur at the boundary stations. At these stations transports are smallest, and thus the effects of velocity errors on total section transport are relatively unimportant. Comparison of two Pegasus vertical profiles of current with profiles obtained from a relative current profiler shows no systematic differences in the vertical structure (*8*).

A trapezoidal-rule integration formula was used to determine total section volume transport from the daily station transport values. We tested the adequacy of this formula qualitatively by assuming a representative cross-stream velocity structure and then moving this structure relative to the fixed station positions. Maximum errors related to the integration formula are of the order of 1 × 10^6 m^3/sec.

Sampling errors are related to the inability of the observing strategy to resolve higher frequency motions. If not adequately resolved, energy at these higher frequencies can be "folded" back into estimates of energy at lower fre-

Table 1. Comparisons of up- and downcast values of the north component of velocity from data collected during September and November 1982 and April and August 1983 and of temperature from data collected during September and November 1982 and April 1983 (a faulty temperature sensor was inadvertently used during August 1983).

Station	Mean difference in northward speed (cm/sec)	Standard deviation (cm/sec)	Mean difference in temperature (°C)	Standard deviation (°C)	Volume transport uncertainty (×10^6 m^3/sec)
0	−0.9	5.5	1.5	1.4	0.04
1	−0.6	4.0	1.5	1.5	0.08
2	3.4	4.9	1.4	1.1	0.16
3	1.2	2.4	1.2	1.1	0.09
4	−1.6	2.2	0.8	0.8	0.13
5	0.5	1.7	0.8	1.2	0.13
6	−1.5	4.0	0.5	0.2	0.28
7	0.0	1.2	0.2	0.1	0.08
8	0.3	4.2	1.0	0.2	0.20