EXHIBIT 1: CODAR STATION LOCATIONS

1. Montauk Point Lighthouse
   Montauk Point, New York
   Suffolk County
   Latitude: 41 deg 4 min 18.8 sec N
   Longitude: 71 deg 51 min 21.8 sec W
   Datum: NAD83

2. Block Island Southeast Lighthouse
   Mohegan Trail
   New Shoreham, Rhode Island
   Washington County
   Latitude: 41 deg 9 min 9.3 sec N
   Longitude: 71 deg 33 min 3.8 sec W
   Datum: NAD83

3. Misquamicut State Beach
   Atlantic Avenue
   Westerly, Rhode Island
   Washington County
   Latitude: 41 deg 19 min 23.2 sec N
   Longitude: 71 deg 48 min 14.5 sec W
   Datum: NAD27

EXHIBIT 2: STATEMENT DESCRIBING THE PROJECT

Agency: Office of Naval Research
National Oceanographic Partnership Program

Project Title: Front Resolving Observational Network with Telemetry

Office of Naval Research Number: N000149911021

Contact Person: Dr. James Eckman
Biological and Chemical Oceanography Program, Code 322BC
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217
(703)-696-4590

Note: The coastal ocean dynamics application radar (CODAR) for which we are seeking a license is task A4 (page 10) in the project proposal that follows this page.

2. Abstract and Table of Partnerships

We propose to develop, demonstrate, and evaluate an easily deployed, cost-effective observation and prediction system for the coastal ocean. A diverse range of real-time physical and biological measurements will be combined with dynamical and biological modeling. The data assimilative approach to ocean observation mitigates the impact of sampling inadequacies by requiring dynamical consistency of the data. It will also allow forecasting.

In situ components of the system will be disturbance-resistant and inexpensive to replace. Data telemetry and instrument control will be accomplished with an underwater acoustic communication network. The network features multiple inexpensive acoustic modems connected in a topology that can tolerate failure or loss of individual elements.

Performance of the observation system will be evaluated by comparing assimilated data products to results from cruises with intense sampling designed to resolve multiple scales of variability.

The demonstration site, on the continental shelf outside of Long Island Sound, is a region of strong tides with energetic wind- and buoyancy-forced motions. The resulting flow field is complex and exhibits a variety of fronts. There is also considerable fishing and commercial shipping that presents a challenge to the instrument network. These features provide an opportunity to test the observation system.

TABLE OF PARTNERS

		Year 1		Year 2		Year 3	
	Roles & Tasks	**NOPP**	**Share**	**NOPP**	**Share**	**NOPP**	**Share**
UConn	Project Coordinator Task A1,A2,A4,B1,B3,C	510,207	[redacted]	667,081	[redacted]	555,480	[redacted]
	Shiptime	56,000	[redacted]	112,000	[redacted]	112,000	[redacted]
MIT	Task A1	46,610	[redacted]	48,870	[redacted]	51,260	[redacted]
WHOI (BO)	Task A6	89,522	[redacted]	86,307	[redacted]	89,747	[redacted]
WHOI (PO)	Task A1	16,391	[redacted]	20,064	[redacted]	21,071	[redacted]
CODAR	Task A4	16,667	[redacted]	16,667	[redacted]	16,667	[redacted]
Datasonics	Task A3	75,000	[redacted]	40,000	[redacted]	25,000	[redacted]
URI	Tasks A4, A5, B1, B2	352,456	[redacted]	214,871	[redacted]	236,108	[redacted]
NUWC	Task B2	100,000	[redacted]	121,400	[redacted]	120,000	[redacted]
USCG	Task B4	0	[redacted]	0	[redacted]	0	[redacted]
SSC-SD	Task A3	140,000	[redacted]	115,000	[redacted]	90,000	[redacted]
TOTAL		1,346,853	[redacted]	1,330,260	[redacted]	1,205,332	[redacted]

3-Year TOTAL Request to NOPP: 3,882,445 **3-Year TOTAL Resource Sharing: [redacted]**

Partner & Task Abbreviations:

UConn	University of Connecticut	Education
MIT	Massachusetts Inst. of Technology	Education
URI	University of Rhode Island	Education
WHOI BO	Woods Hole Oceanographic Inst. (Biological Oceanography)	Education
WHOI PO	Woods Hole Oceanographic Inst. (Physical Oceanography)	Education
CODAR	Codar Ocean Sensors, Ltd.	Industry
Datasonics	Datasonics, Inc.	Industry
NUWC	Naval Undersea Warfare Center	Government
SSC-SD	Space and Naval Warfare Systems Center, San Diego	Government
USCG	United States Coast Guard	Government

Task A1	Data assimilation and inverse modeling
Task A2	Autonomous, trawl-resistant, bottom-mounted instrument array
Task A3	Bottom-mounted acoustic communications network
Task A4	High-frequency radar measurement of surface currents (CODAR)
Task A5	Satellite temperature (AVHRR) and color (SeaWiFS)
Task A6	Profiling plankton observatory
Task B1	Large scale surveys
Task B2	Frontal scale turbulence survey
Task B3	Frontal scale circulation and hydrography
Task B4	Lagrangian drifter program
Task C	Educational outreach

Section 3.

3a. Relevance of Project to Critical NOPP Objectives

The "Front Resolving Observational Network with Telemetry" (FRONT) project will develop, demonstrate, and test a physical and biological observation capability in the coastal ocean. The anticipated real-time products will include continuous, high resolution and dynamically consistent observations. Autonomous real-time measurements of physical and biological variables, both in-situ and remotely sensed, will be coordinated with assimilative dynamical modeling. FRONT partners will work together toward the following specific goals that are relevant to NOPP objectives:

(1) Adapt the recently developed non-hydrostatic data-assimilative MIT general circulation model (MITgcm) to the coastal ocean for the first time (Task A1),
(2) Apply and develop new underwater data acquisition and acoustic communication technologies (Tasks A2 & A3),
(3) Develop improved methods for high-resolution remote sensing of surface current with high-frequency radar (Task A4),
(4) Develop and apply new methods for real-time acquisition of a suite of plankton and hydrographic measurements (Task A6),
(5) Develop and apply new techniques for measurement of turbulence with an AUV (Task B2),
(6) Develop and apply techniques for measuring frontal features in hydrography and velocity (Task B3),
(7) Test the data assimilation and prediction capabilities of the observation system by surveys, including Lagrangian drifter deployments, with U.S. Coast Guard participation at no cost to NOPP, and
(8) Provide near real-time data and data assimilation products for outreach and education. (Objective C).

The FRONT project will coordinate real-time data products several ongoing educational outreach programs, including: (1) an EPA funded EMPACT project at UConn project coordinated by Dr. Frank Bohlen, (2) The Jason Foundation, and (3) The Rutgers University Institute of Marine and Coastal Sciences. In addition, the president of The Southern New England Fisherman and Lobsterman Association, Arthur Madeiros has agreed to assist in coordinating a meeting with trawlers and scallop draggers who fish in the area of the FRONT site. (Letters attached.)

The measurement and data communication techniques, modeling, and data assimilation employed in FRONT will complement other on-going NOPP programs. In particular, FRONT partners are committed to working with Rutgers University, a past recipient of NOPP funding, toward implementation of a regional distributed observation network for the Middle Atlantic Bight. (Letter from PI Scott Glenn attached.)

3b. Broad participation within the oceanographic community.

Investigators from a broad spectrum of educational backgrounds working at small and large oceanographic institutions, in private industry, and at government laboratories propose this program. Table 3.1 demonstrates this breadth and diversity by summarizing each investigator's institution and research area.

Table 3.1 Participation within the oceanographic community.

PI	Research Area	Organization
P. Bogden	Coastal Inverse modeling & data assimilation	University of Connecticut
D. Codiga	Shelf dynamics	
J. O'Donnell	Coastal ocean front dynamics & observations	
I. Babb	Coastal Ecology and ROV Applications	
P. Cornillon	Remote sensing	University of Rhode Island
D. Hebert	Turbulence and mixing	
P. Steggman	Remote sensing and ocean color	
S. Legg	Ocean modeling	Woods Hole Oceanographic Inst.
S. Gallager	Zooplankton ecology	
H. Sosik	Phytoplankton ecology	
J. Marshall	Ocean modeling	Massachusetts Inst. of Technology
M. Follows	Biochemical ocean modeling	
E. Levine	Turbulence and mixing, AUV	Naval Undersea Warfare Center
J. Dick-O'Donnell	Remote sensing in Search and Rescue	United States Coast Guard Research and Development Center

Table 3.1 Participation within the oceanographic community.		
PI	**Research Area**	**Organization**
P. Bogden	Coastal Inverse modeling & data assimilation	University of Connecticut
D. Codiga	Shelf dynamics	
J. O'Donnell	Coastal ocean front dynamics & observations	
I. Babb	Coastal Ecology and ROV Applications	
P. Cornillon	Remote sensing	University of Rhode Island
D. Hebert	Turbulence and mixing	
P. Steggman	Remote sensing and ocean color	
S. Legg	Ocean modeling	Woods Hole Oceanographic Inst.
S. Gallager	Zooplankton ecology	
H. Sosik	Phytoplankton ecology	
J. Marshall	Ocean modeling	Massachusetts Inst. of Technology
M. Follows	Biochemical ocean modeling	
E. Levine	Turbulence and mixing, AUV	Naval Undersea Warfare Center
J. Dick-O'Donnell	Remote sensing in Search and Rescue	United States Coast Guard Research and Development Center
P. Herring	Lagrangian drifters in Search and Rescue	
D. Porta	Acoustic modems	Datasonics Inc.
J. Rice	Telesonar communications	Space and Naval Warfare Systems Center SD
B. Lipa	HF radar measurement of surface current	Codar Ocean Sensors, Ltd.
D. Barrick	HF radar measurement of surface current	

3c. Long-term commitment to the proposal objectives.

All four academic institutions involved in this project (UConn, URI, WHOI and MIT) have a well-established record in oceanographic research and education. Recently, both the State of Connecticut and the State of Rhode Island strengthened their commitments by funding the construction of new facilities to further these activities. The newly built and commissioned R/V Connecticut provides a significant symbol of Connecticut's commitment to coastal oceanographic research.

Further institutional commitment to the NOPP objectives is indicated by the matching funds for the purchase the new equipment required by the FRONT project (Table 3.2). In addition, the institutions have committed considerable existing resources at no cost to NOPP.

The individual principle investigators have demonstrated an intellectual commitment to the NOPP goals. The collaborative development of the model and data assimilation methods at UConn and MIT (Bogden and Marshall) has been underway since 1996 and they have been applied to Long Island Sound (Bogden and O'Donnell). Similarly, the satellite remote sensing group at URI (Cornillon and Ullman) and the coastal physical oceanography groups at UConn and URI (O'Donnell, Hebert and Codiga) have decades of effort committed to coastal ocean observation systems.

3d. Resources shared among partners.

The major new hardware components of the observation system will be shared resources during the duration of the program. With UConn equipment match, the project will purchase an SGI Origin 2000 computing system to be used for data assimilation and modeling by UConn, WHOI, and MIT investigators. The deployment and maintenance of the CODAR system will be the shared responsibility of URI and UConn. The acoustic network will service instruments deployed by UConn, URI, WHOI, and the Navy. The Navy will provide all acoustic network hardware during year one at no cost to NOPP. This will allow us to purchase new hardware in year two that will be redesigned to meet Navy specifications resulting from year-one efforts. All data and analysis products will be served on the Internet from UConn, where two full-time personnel (technician and programmer) are to be supported.

3e. The degree of cost sharing by partners with the requested Partnership funding.

The University of Connecticut demonstrates its long-term commitment to coastal oceanography and NOPP objectives with a total cost share of $663,115 -- more than double the expected indirect costs. Of this, $375,000 will go toward permanent equipment that will serve all FRONT partners. $280,045 will provide electrical and mechanical engineering support for the overall program, and one full-time UConn graduate research assistantship at no cost to NOPP.

The University of Rhode Island similarly demonstrates its commitment with $235,475 of cost share, much of which will go toward purchase of the CODAR HF radar. This will provide an integral component of the real-time data streams to be used by all partners.

The Woods Hole Oceanographic Institution offers 30% cost share for equipment and salaries in their biological and physical components of FRONT, totaling $138,443.

The Space and Naval Warfare Systems Center, San Diego, provides a total cost share of $1,910,000 through modification of its ongoing telesonar research program to the needs of the FRONT program. The Navy is committed to executing a series of annual experiments under an operational concept known as "SeaWeb," which includes basic research in acoustic signaling and acoustic channel modeling. SeaWeb involves multiple Small Business Innovation Research contracts, and had approximately $1M of FY98 funding. FRONT will leverage these developments by offering the Navy an unclassified application that has similar demands to the Navy's envisioned littoral surveillance applications. In turn, the Navy pledges to direct telesonar resources, including all modem hardware in year one, to the demands of the FRONT project. SeaWeb will exercise the early FRONT network and ensure a high probability of success during its subsequent deployments. In this symbiotic partnership, SSC-SD and Datasonics bring added participation of Delphi, SAIC and Northeastern University. The SSC-SD and Datasonics requests to NOPP provide resources necessary to develop and maintain the long-term applications intended for FRONT.

The United States Coast Guard Research and Development Center offers the entire surface-drifter component of FRONT (Task B4) at no cost to NOPP. The estimated $180,000 contribution to NOPP includes costs associated with aircraft, buoy tenders, ARGOS data recovery, and personnel for 3 years of participation, plus the purchase of 10 self-locating data marker buoys (SLDMBs).

CODAR Ocean Sensors will provide resource sharing of $151,000 which includes salary for Drs. Don Barrick and Belinda Lipa to aid in the development of improved algorithms for providing high resolution current maps from HF radar (Task A4).

Section 4. Description of Research Program

4.1 Scientific Background and Motivation.

It is clear that variations in the circulation and important biological and physical fields such as nutrients, temperature, and salinity can occur on very small scales in the coastal ocean. These show up in satellite observations of ocean color and surface temperature. Regions of sharp gradients are often termed "fronts" and can have scales in the range of one meter to ten kilometers. An example of ocean color along the Northeast seaboard (Figure 1a) shows front locations as determined by an edge-detection algorithm. This algorithm applied to more than a decade of satellite-derived sea surface temperature (SST) reveals localized areas of intense frontal activity (Figure 1b; Ullman and Cornillon, 1999). Persistent gradients are found throughout the entire region and are associated with zones of productive fisheries around Georges Bank, and with the shelf break. There is also a recurrent inner-shelf front offshore of Block and Long Islands, perhaps associated with outflow from Long Island Sound.

Fronts in coastal waters are often sites of enhanced primary and secondary production and increased concentrations of biogenic and other particles. (Cushing, 1975; Denman and Gargett, 1995; and Gallager et al., 1996 give reviews). Theories of the dynamics of the phenomena distinguish between various mechanisms of frontal formation (O'Donnell, 1993, reviews the subject) but all are ambiguous about the important spatial scales. The work of Linden and Simpson (1988) suggests that a horizontal gradient in density will have a tendency to create small scales through nonlinear self advection of the density fields.

However, detailed observations that resolve the across-front scales have been few. Recent observations of river plume fronts directly verified frontal scales of order 10 m, strong surface convergence, and downwelling rates of order 10 cm/s (O'Donnell et al., 1998). Such small regions of intense vertical fluxes and mixing are likely to exist at other types of fronts. An improved ability to measure and model fronts is needed to better understand and assess the significance of these phenomena.

To complement other coastal ocean observation systems, we propose to develop, implement, and evaluate a front resolving observational network with telemetry (FRONT) in a region of complicated dynamics. Data assimilative modeling will be an integral component of the observation system and will provide predictive capabilities. The demonstration site lies outside the mouth of Long Island Sound in a region strongly influenced by estuarine outflow and tidal currents (Figure 1b). Small-scale fronts often observed there are characteristic of many documented examples from outside the mouths of most major U.S. estuaries including the Chesapeake and Delaware Bays and the Columbia, Mississippi and Hudson Rivers. The approaches to these estuarine areas are of considerable national importance for fishing, navigation and commerce, and naval activities. However, observing and modeling them is a significant technical challenge. The wide variety of spatial scales can not properly be resolved in standard model grids, and the cost of a densely instrumented *in situ* array is prohibitive. The observation system we propose represents a substantial advance in the use of a real-time data collection network in concert with a dynamical model. Observational and predictive capability in four dimensions will be obtained with data-assimilative modeling designed to resolve or parameterize the needed range of scales. Our system will complement existing observation platforms, such as LEO-15 of Rutgers University, that have been developed at dynamically simpler sites.

4.2 Project Overview.

There are two primary objectives in FRONT: (A) to develop and implement a coordinated autonomous coastal observation system in which real-time data streams are assimilated into a regional dynamical and biological model; and (B) to evaluate the observation system with ship and AUV (autonomous underwater vehicle) surveys covering a range of scales from tens of kilometers to meters. An education and public outreach program, Objective C, will distribute products based on the project results in near real time.

A four-dimensional picture of the circulation will be obtained by assimilating data into a regional physical-biological model (Task A1). This long-term observational capability will be demonstrated by providing observations continuously for a nine month period in project year three. Real-time data streams for assimilation will include remote sensing to provide maps of surface properties, and sub-surface sampling to provide profiles in the water column. Measured surface properties will include currents from shore-based HF (high frequency) radar (Task A4), and satellite observations of surface temperature and color (Task A5). Sub-surface measurements will include vertical profiles of currents and hydrography (Task A2) and, biological and optical variables (Task A6). The capability for long-term observations requires an easily maintained, disturbance-resistant instrument array in which all elements have minimal water-column exposure. Therefore, sensors will be mounted on the ocean bottom in trawl-resistant housings. Velocity profiles will be obtained acoustically with ADCPs (acoustic Doppler current profilers). Hydrography and biology will be sampled with profilers that reside in protective housings on the bottom when not active. In a novel technological application, the entire suite of bottom-mounted sensors will telemeter their data to shore in real time via a distributed network of bottom-mounted acoustic modems (Task A3). The subsurface network will provide multiple redundant and adaptive communication paths to accommodate individual instrument and transponder failures. Moreover, two-way network communication with instruments will allow adaptive sampling strategies.

The abilities of the observational system will be evaluated through ship-based and AUV surveys, and by a series of surface drifter deployments. High-speed towed-body surveys will provide quasi-synoptic 3-D pictures of circulation and hydrography on the regional (Task B1) and frontal scales (Task B3). Towed and AUV-based microstructure instruments will describe the distribution of vertical turbulent fluxes (Task B2). The Lagrangian drifter deployment (Task B4) will provide a means to evaluate improvements to the CODAR algorithms (Task A4) and the skill of the observation system in predicting Lagrangian trajectories.

4.3 OBJECTIVE A: Real-Time Observation System

TASK A1: Inverse modeling and data assimilation

Motivation. The capability for long-term four-dimensional ocean observation and prediction requires integration between data and modeling. But the quantity and kinds of data required to obtain a given accuracy remain unclear. These concerns are shared by any environmental monitoring effort, and WOCE-related programs are addressing such issues on a global scale. Our goal is to build upon such experience and implement a data-assimilative observation system for the biology and physics of a dynamically complex region of the coastal ocean. We will also address the unique challenges associated with providing that capability in real time for extended periods.

Proposal: We propose to provide a coordinated and dynamically consistent presentation of real-time data from a diverse range of instruments measuring biological and physical quantities. We will also evaluate the associated data requirements for an autonomous measurement program. Inverse modeling and data assimilation provide two distinct and complementary steps toward these overall goals.
Inverse modeling: The inverse method proposed here (Bogden and O'Donnell, 1998; Bogden et al., 1996) provides an extremely efficient analysis tool that will be automated to produce real-time velocity maps and associated error fields. The generalized inverse method (see Bennett, 1992) will combine surface velocity (Task A4) and ADCP velocity profiles (Tasks A2 & A3) with linearized shallow-water dynamics. ADCPs provide good vertical resolution with poor horizontal resolution, while CODAR provides good horizontal coverage of the surface only. The inverse will provide a statistically optimal combination of the two, yielding a dynamically consistent depth-averaged velocity field over a large horizontal domain. Further statistical analysis (Bretherton et al., 1976) of CODAR data will produce optimal estimates of surface velocity and its errors. This can extend the useful coverage of CODAR data by providing velocity maps in regions where CODAR sensors provide only one component of velocity. Furthermore, the statistical foundations of the inverse method permit straightforward evaluation of sampling strategies that will aid instrument placement (Task A2) and ship tracks (Task B1). The inverse will also provide barotropic boundary conditions for the data assimilation described below. The calculations will be performed on the existing four-processor SGI Origin 200 computer that will also serve all data products to the Internet.

MITgcm: The MIT general circulation model (MITgcm), developed recently by Dr. John Marshall (MIT) and colleagues (Marshall et al., 1997a and 1997b), has been successfully applied in a variety of large-scale climate-related circulation problems. MITgcm will be adapted to the coastal ocean for the first time during FRONT. It has several novel features that make it especially suited for modeling coastal circulation. These include (1) a non-hydrostatic capability, (2) an accurate finite-volume representation of steep bathymetry, (3) an efficient adjoint model for the tangent-linear (linear perturbation) equations, and (4) an efficient modular design that makes the code versatile and portable.

The non-hydrostatic capability of MITgcm positions it to make substantial advances when it is adapted to a coastal region. Non-hydrostatic dynamics can be important in areas of strong convergence and divergence associated with fronts, and also in large aspect ratio flows near topography, such as internal bores due to tidal motion. To capture dynamically similar flows, modern mesoscale atmospheric models are almost universally non-hydrostatic. MITgcm includes the Large et al. (1994) nonlocal "K profile parameterization" (KPP) of vertical mixing by unresolved scales.

The proposed modeling is a natural follow-on to present ONR-funded work of Dr. Sonya Legg (WHOI) on baroclinic motion near steep topography with open boundary conditions (Legg and Wunsch, 1999). Legg will help adapt MITgcm to the FRONT region. This will be an important application of the "finite-volume" numerical method which makes possible a novel treatment of irregular boundaries (Marshall et al., 1997b and Adcroft et al, 1997). Moreover, the domain-decomposition modularity employed in the model will enable straightforward investigation of nested-grid simulations on parallel computers.

Data assimilation: MITgcm's adjoint and tangent-linear formulation will be used for data assimilation. They will be adapted to assimilate real-time data streams including profiles of hydrography and velocity (Task A2), CODAR surface velocity (Task A4), and satellite-derived surface temperature (Task A6). The

MITgcm adjoint has demonstrated success on ocean-basin scales with assimilation of satellite altimetry data (Stammer and Wunsch, 1994) and the assimilation of hydrography and surface fluxes (Lee and Marotzke, 1998). FRONT will benefit from these studies, which have shown that initial conditions and boundary-forcing conditions can be obtained with a variety of data types. Predictability will be evaluated with real-time data streams and survey data (Objective B).

MIT partners will provide analysis products from independent collaborative large-scale state estimation efforts involving MIT, the Jet Propulsion Laboratory and Scripps Institution of Oceanography. Data-assimilation products will include baroclinic open boundary conditions and initial conditions from the high-resolution North Atlantic model. These will supplement barotropic boundary conditions from the FRONT inverse analysis described above. Thus, the adjoint method for assimilation with MITgcm will benefit from a starting point for the 4-D assimilation that is already "close" to the observations.

Biological modeling: Dr. Mick Follows (MIT) will work with biologists at WHOI and URI to adapt the biogeochemical aspects of MITgcm to an appropriate ecosystem model. UConn is providing, at no cost to NOPP, a graduate research assistanship to aid in this task. Follows has been using MITgcm for global-scale biogeochemical modeling (e.g., Follows and Marshall, 1999; Follows et al., 1996), and will assimilate satellite color (Task A5) and *in situ* biological data from the plankton observatory (Task A6).

Drs. Philip Bogden (UConn), Sonya Legg (WHOI), John Marshall (MIT), and Mick Follows (MIT) will work together to implement the full data assimilative capabilities of MITgcm. The MITgcm and inverse-model domains will be substantially larger than the instrument array. A 3-day prognostic model run with 200x200x50 grid points and half-kilometer resolution requires 500 CPU hours. The computational requirements of the adjoint model are substantially greater at 4 times as much memory and 3 times as much CPU. MITgcm runs very efficiently on a wide variety of platforms, including SGI multiprocessor systems. Existing four-processor Origin 200s at both UConn and WHOI will be used for moderate-resolution preliminary calculations, visualization, and diagnostics. In year two, a twelve-processor SGI Origin 2000, purchased with UConn equipment match, will offer full compatibility with the smaller SGIs, and will permit the more computationally intensive data assimilation. SGI has offered technical assistance to further optimize the code for their platform, if necessary, at no cost to NOPP. SGI has also offered the FRONT project a special 50% hardware discount.

Anticipated results. Data streams from tasks A2, A5 and A6 will be integrated into dynamically consistent 4-dimensional fields of velocity, hydrography and biological parameters. The goal is to produce these fields in near real time. These results will feed back on efforts to improve the HF radar algorithms (Task A4), front-tracking algorithms with satellite images (Task A5), and Objective B sampling strategies.

TASK A2: Autonomous, trawl-resistant, bottom-mounted instrument array

Motivation: An instrument array that collects long-term time series of vertical profiles of physical and biological properties in near real-time is central to coastal ocean observation and modeling systems. However, present mooring technologies are not adequate for extended deployments in coastal waters typified by strong tidal and wind-driven currents, intense surface wave activity, and heavy commercial fishing and shipping. There is a clear need for an array of profiling instruments with minimal water-column exposure that telemeters data to shore over a channel that is both robust to bottom-trawling and easily maintained for long periods.

Proposal: An array of autonomous bottom-mounted ADCP and profiling CTD instruments will be deployed for periods of up to nine months (Figure 1c). The array will include seven ADCPs and two CTD profilers, and an autonomous vertically profiling plankton observatory (AVPPO, Task A6 below) located at its center. The ADCP array spans a region 18 km across in both along- and across-shelf directions. The CTD profilers are positioned along an across-shelf transect including the AVPPO, which also measures hydrographic profiles. NOPP support is requested to acquire three 600 kHz RDI Workhorse ADCPs in year two and to acquire two OceanSensors CTD profilers in year one. The ADCPs will complement four 300 kHz RDI ADCPs made available by O'Donnell (UConn) at no cost to NOPP.

All instruments will implement two-way wireless communication in near real time with a data center at University of Connecticut. An adaptive subsurface network of acoustic modems (Task A3) will serve the ADCPs and AVPPO. A modem-ADCP data logger interface will be developed at UConn. The CTD profilers will surface and telemeter their data to a bluff high on Block Island by RF link using a compliant antenna, an off-the-shelf capability provided by OceanSensors.

Two-way communication with shore will permit adaptive sampling choices for all instruments in near real time. To satisfy the needs of the assimilative modeling and the data rate limitations, nominal ADCP sampling will consist of 2-m vertical bin size with 10-minute ensemble averages. CTD profiles taken four times daily with 5-cm averaging will provide the background hydrography for data assimilation. Dr. Dan Codiga (UConn) will be responsible for array data streams, including processing, archiving, Internet distribution, and analysis. Computing resources will be an existing SGI Origin 200 at UConn.

UConn engineers will adapt their existing design for trawl-resistant bottom mounts to accommodate the type of trawling expected at the FRONT site. In the initial array deployment, these new prototypes will be tested by a variety of trawlers with cooperation from the local fishing community. This will be coordinated by Babb (NURC-UConn) as part of the Education and Outreach component of the program (Objective C below). Each instrument, including repeater modems, will be deployed in a trawl-resistant bottom mount. We request NOPP funding for bottom mounts at the rate of $1K per unit, a substantial savings from the price of commercially available products, and also for an acoustic release, float with line, and pinger to enable recovery and servicing of each bottom mount. UConn will provide engineering design and testing as part of the cost sharing agreement.

Codiga (UConn) will carry out array deployment, maintenance, and recovery with UConn technicians using the newly commissioned R/V Connecticut based in Groton, CT, 2-3 hours steam from the FRONT site. An ROV under the direction of Ivar Babb (NURC-UConn) will provide a secondary means of servicing and recovery in the event of acoustic-release failure. The ROV time will be provided by NURC at no cost to NOPP. Three-month servicing intervals are required by battery limitations, and additional ship time is budgeted for servicing of damaged instruments. Real-time network interrogation from shore will allow disruptions to be detected promptly. Loss of individual modem-repeater nodes will not affect the real-time data recovery because of the availability of auxiliary data paths (see Task A3).

Four deployments are scheduled (Table 3). In the first year, subsets of the array will be tested during a two-month deployment in early winter and a three-month deployment in spring. In the second year there will be a six-month deployment of the entire array, with one scheduled servicing after three months. The program will culminate in a nine-month deployment in the third year, with two scheduled servicings. Ship time requirements are 4 days for deployments, 3 days for recoveries, and 4 days for servicing.

Anticipated results. The array will supply the observation system with a real-time data stream of velocity and hydrographic profiles. New low-cost trawl-resistant bottom mounts will incorporate results of trawling tests by the local fishing community. We will demonstrate bottom-mounted instruments that are of general utility in coastal waters because they measure profiles of velocity and hydrographic variables, have minimal water column exposure, and facilitate two-way wireless communication with shore in real-time.

TABLE 3. FRONT program calendar

<table>
<tr><th>Year</th><th>A</th><th>S</th><th>O</th><th>N</th><th>D</th><th>J</th><th>F</th><th>M</th><th>A</th><th>M</th><th>J</th><th>J</th></tr>
<tr><td>1: 1999-2000</td><td>SeaWeb99</td><td></td><td></td><td colspan="2">FRONT1</td><td></td><td></td><td colspan="3">FRONT2</td><td>SeaWeb00</td><td></td></tr>
<tr><td>2: 2000-2001</td><td></td><td colspan="6">FRONT3</td><td></td><td></td><td></td><td>SeaWeb01</td><td></td></tr>
<tr><td>3: 2001-2002</td><td></td><td colspan="9">FRONT4</td><td></td><td></td></tr>
</table>

TASK A3: Bottom-mounted acoustic communications network

Motivation: Observation of shelf circulation requires instruments distributed over tens of kilometers. The reliable delivery of data to shore from such an array in near real-time is a technological challenge. Cabling is expensive, inflexible and vulnerable to commercial trawling. Vulnerability of surface buoys to weather, rough seas, and human intervention discourages use of telemetry by radio or satellite links. Recent rapid developments in digital communication techniques make an autonomous network of undersea acoustic modems a cost-effective alternative. It has the additional advantage of adaptability to the loss or failure of individual array components.

Proposal: We propose to develop and implement an undersea data communications network that enables two-way near real-time communication between instruments and an onshore data center. The network will feature multiple alternative paths between each instrument in the profiling array and the data center. It will therefore be tolerant of damage to individual components. The project will be coordinated with ongoing ONR-funded efforts by Dr. Joe Rice of the Space and Naval Warfare Systems Center, San Diego (SSC-SD) that advance "telesonar" digital communications for Navy use in adverse undersea acoustic channels such as those existing between instruments in the profiling array.

The network elements will include instrument nodes, repeater nodes, and gateway nodes on nearby Coast Guard buoys that communicate with shore (Figure 1c). Each ADCP in the array, and the AVPPO, will be deployed with an acoustic modem to form an instrument node. The repeater nodes will facilitate communications between the instrument nodes and the gateway nodes and provide each instrument with multiple acoustic paths to shore. The network will then be able to adapt its communication paths to the loss of individual array elements, providing robustness against such disturbances.

Telesonar technology is evolving with the specific intent to support autonomous sensor networks having similar topologies and throughput requirements to that of FRONT. Telesonar signaling is inherently channel-tolerant, and ongoing developments will provide adaptive modems that probe the channel, estimate the prevailing propagation parameters, and optimize the modulation for maximum link capacity and energy efficiency. This approach is preferred over adaptive demodulation because of battery-energy constraints for long-term deployments. Telesonar networks support packetized data telemetry from the network as well as remote control and interrogation of specific instruments from ship and shore sites or via the internet.

FRONT will leverage Navy efforts to develop Telesonar by providing an unclassified application having similar demands to envisioned littoral surveillance applications. In turn the Navy pledges to direct telesonar resources to the demands of the near-term FRONT installation in a symbiotic partnership. At no cost to NOPP, the annual SeaWeb experiments will implement, demonstrate, and test the telesonar network topology intended for FRONT deployments. Thus, SeaWeb will exercise the intended FRONT network and ensure a high probability of success during its subsequent deployments. SSC-SD, Datasonics, Delphi, SAIC, and Northeastern University join the FRONT team with responsibilities for network design and implementation.

In NOPP year one, the site will be extensively analyzed for acoustic propagation and optimized node placement. Prior to initiating network design, the means to define and compress communication packet content will be arranged by partners responsible for the profiling array. A frequency-division multi-access (FMDA) network will be designed for FRONT, extensively simulated, and implemented during SeaWeb'99 in Buzzards Bay during August 1999. Next, the Navy and Datasonics will provide modems on loan for a two-month installation at the FRONT site (Nov-Dec 99). Selected modems will be integrated with FRONT instruments in this initial engineering trial. A larger subset of the array and network will be re-deployed later in spring for three months (Mar-May 00). These two deployments will provide acoustic performance measures under conditions representative of seasonal extremes. Also in year one, UConn engineers will install gateway modems and cell phone links on the USCG Montauk Point and Southwest Ledge navigation buoys, with cooperation from the Coast Guard. Existing cell phone coverage permits 19.2K TCP/IP connections from these locations as has been confirmed by a visit with a UConn vessel to test data transmission.

In year two, the next-generation telesonar modem now being developed under SSC-SD contract will become commercially available from Datasonics, Inc. NOPP funding is requested to procure modems for dedicated use during years 2 and 3 of FRONT. These will be incorporated as SeaWeb2000 assets for thorough testing and evaluation, including full integration of FRONT instruments. SeaWeb2000 (June 2000) will introduce major advancements in telesonar network protocols, including code-division multiuser access (CDMA) node addressing. After SeaWeb2000, the FRONT array will be deployed for six months (Sep 00-Feb 01). In year three, the acoustic network will be redesigned following extensive analysis of data gathered to date. This transition offers the Navy an opportunity to upgrade the modems and network protocols with the latest evolution of technology. The network and profiling array will be tested again by the Navy during SeaWeb2001 (Jun 01), and the final nine-month FRONT deployment will ensue (Sep 01- May 02).

Anticipated results. A distributed and autonomous network of acoustic modems will demonstrate bi-directional acoustic communication between the shore and sparsely located in situ instruments in near real-time. The subsurface, wireless nature of the network represents a significant advance for data relay to shore in the challenging environment of coastal waters. Mutually beneficial coordination of resources between Navy SeaWeb and FRONT deployments will lead to improvements in telesonar modem functionality for this application.

TASK A4: High-frequency radar measurement of surface currents (CODAR)

Motivation: Spatial resolution of currents for high quality data assimilation is not obtainable from moored instruments or satellite platforms. Shore-based HF radar techniques permit broad spatial coverage of surface currents within line-of-sight ranges of the coast. The coordinated observation system will facilitate advances in this critical measurement technique that help increase its resolution and move toward the capability to resolve frontal features in the coastal ocean.

Proposal: Surface current maps from the Coastal Ocean Dynamics Application Radar system will be a primary component of the FRONT real-time data streams. CODAR uses HF radar to remotely sense surface current up to 70 km from shore-based antenna sites (Barrick et al., 1977). Each three-antenna SeaSonde unit from CODAR Ocean Sensors Ltd. has a compact whip and crossed-loop antenna combination that senses the radial component of the flow, relative to the SeaSonde, within its unobstructed field of view. Two SeaSonde sites provide both velocity components at locations that are not co-linear with the antenna sites and can nominally achieve spatial resolution of a kilometer.

CODAR will be central to the FRONT observation system. The primary goal, therefore, is to deliver surface velocities for assimilation. Secondary goals will be to improve the algorithm used in the estimation of surface velocity vectors and to establish the statistics of their errors.

The proposed positions of three CODAR antenna sites are at Block Island, Montauk Point, and Watch Hill Point (Figure 1b). All are Coast Guard lighthouses offering secure shorefront locations with access to shelter, power, and telephone. These sites afford coverage of greater Block Island Sound and the eastern end of Long Island Sound, where historical observations indicate strong exchange flows.

We propose to advance CODAR technology by improving upon the algorithm used to obtain currents from the radar backscatter. The greatest source of error in surface current maps produced by any HF radar lies in determination of bearing angle for radial currents observed at a SeaSonde site. Drs. Dave Ullman (URI) and Philip Bogden (UConn) will work together with Drs. Don Barrick and Belinda Lipa (CODAR Ocean Sensors) to improve the present algorithm (MUSIC) by examining three issues. (1) The azimuthal degrees of freedom may be increased by keeping separate the spectral information associated with reflection from outgoing and incoming surface waves. This could potentially increase azimuthal resolution by more than a factor of two. (2) MUSIC assumes the noise covariance is diagonal. However, there are several possible explanations for a non-diagonal covariance, including finite sample size and multiple incompletely resolved bearing angles from small-scale current features. The signal covariance can be simulated with surface velocity fields from data-assimilation products and then compared with signal variance obtained from actual CODAR time series. The long times series planned would make such analysis possible. This type of analysis could lead to more reliable criteria for determining the number of significant bearing angles with MUSIC. (3) Present implementations of MUSIC solve for radial velocities and azimuthal angles one range bin at a time. This approach is "local" in the sense that all bins are treated independently of each other. We propose to implement a hierarchy of "global" physical constraints by solving for the entire velocity field at once using an iterative method. This will extend early work by Lipa and Barrick (1983) for providing velocity maps.

In year one, NOPP funds will be applied to the purchase and installation of three SeaSonde sites, including training of Dr. Dave Ullman (URI) and a technician in its use and maintenance. Real-time data streams will come on-line and be distributed for research and public outreach. Ullman (URI) and Bogden (UConn) with work with Lipa and Barrick (CODAR Ocean Sensors Ltd.) to develop new algorithms and improvements to MUSIC. Twice yearly meetings at URI of academic and industry partners will be coordinated without need for NOPP funds. In years two and three, algorithmic development will continue at levels of year one. Improved algorithms for velocity mapping will be implemented in MATLAB so they can be easily distributed.

Anticipated results. CODAR surface velocity fields will provide an essential real-time data stream in the observation system. In turn, because other independent data streams will be incorporated, the data-assimilative model results will provide an important means by which to constrain the CODAR error fields. Results of testing and modification of CODAR algorithms to improve horizontal resolution will be distributed to the oceanographic community for general use and continued development.

TASK A5: Satellite ocean color (SeaWiFS) and temperature (AVHRR)

Motivation: Established, ongoing satellite measurement programs collect ocean color and sea surface temperature fields with extensive coverage and resolution down to about one km. These data streams provide direct measures of critical biological and physical aspects of the coastal ocean system. Integrating them together with other observations in a data assimilation program not only improves the modeling but also permits key advances in interpreting processes that control patterns in the satellite data fields themselves.

Proposal: There are three objectives for the satellite observations: (1) to relate them to in situ data, thereby revealing the 4-D structure associated with frontal features observed in the remotely sensed fields, (2) to provide surface fields for data assimilation in order to assess frontal dynamics, biological significance, and predictability, and (3) to provide ocean color and SST images for design of sampling strategies of field surveys (Objective B) for system evaluation. Image products will include maps of front locations as determined by an edge detection algorithm (Cayula and Cornillon, 1995). The real-time satellite images will establish a contribution to the public outreach and education component that should continue beyond the 3-year NOPP project.

SeaWiFS ocean color. Remotely sensed ocean color provides a measure of near surface phytoplankton pigment. Enhanced biological activity near ocean fronts is well-documented (Nihoul, 1986, Sournia, 1994), and images from satellite ocean-color sensors are known to exhibit frontal patterns on the continental shelf (Dupouy et al., 1986). Ocean color fronts in historic Coastal Zone Color Scanner data have been compared with multi-year SST front data in the inner shelf waters of the proposed site, and it has been shown that the spring-summer period has the highest occurrence of concurrent chlorophyll and thermal fronts (Chan and Yoder, 1999). Satellites are useful platforms for observing such ecosystem variability. However, there is little knowledge of the relationship between satellite observations and in situ distributions such as velocity and density fronts. These can concentrate particulate matter of both natural and anthropogenic origins, including plankton, harmful algal blooms, and oil spills.

SeaWiFS (Sea-viewing Wide Field-of-view Sensor) is a NASA ocean color sensor that has been transmitting images since September 1997 (McClain et al., 1998; Hooker et al., 1993). Figure 1a shows a typical SeaWiFS ocean color image showing numerous small-scale structures in the phytoplankton chlorophyll distribution over the southern New England shelf. Superimposed are chlorophyll fronts as determined with the URI edge-detection algorithm. Dr. Petra Steggman (URI) will apply her experience with SeaWiFS data to integrate it in the FRONT observation system. A focus will be to establish the relationships between frontal features in ocean color and water-column fields.

AVHRR temperature. With NASA funding, the URI remote sensing group used the NOAA/NASA SST algorithm to reprocess all available 5-channel AVHRR satellite passes over the western North Atlantic from 1985-1996. This produced SST fields covering the US East Coast twice each day with 1-km resolution, clouds permitting. Declouding and edge-detection algorithms yielded a 12-year time series of frontal positions and gradient magnitudes (see Figure 1b). The long time series indicates that SST fronts are ubiquitous in winter on the inner shelf along the entire coast from Cape Hatteras to Nova Scotia (Ullman and Cornillon, 1999; Ullman et al., 1999). However, the 12-year AVHRR SST time series has sufficient data gaps, often due to cloud cover, that we have no reliable method for tracking individual fronts from image to image. As a result, we have little information about the lifetime and dynamics of these SST fronts, which potentially have significant control over the distribution of materials on the inner shelf.

Assimilation of the entire suite of real-time data streams, including those from satellites, into a dynamical model will address several unresolved issues about these satellite analyses. These include the nature of the velocity field associated with the satellite observations, the underlying dynamical mechanisms, and the relationships to biological variables. Assimilative modeling will also establish the connection between features observed in successive satellite images. This information on time scales for frontal formation and decay will be used to optimize the algorithm for tracking fronts from image to image. Such an algorithm has broad applicability, especially with regard to inference of surface velocity by feature-tracking.

In all three years, color and SST images, along with frontal maps obtained with the edge-detection algorithm, will be provided to partners and public outreach in near real-time. The URI remote sensing group has provided such support on a number of occasions in the past (e.g. SYNOP and FASINEX projects). The synoptic images will be used to plan and carry out the field surveys. Drs. Petra Steggmann, Peter Cornillon, and Dave Ullman (all of URI) will work with other academic partners and apply satellite products to the observation system, including identifying the best method of assimilating SST data.

Anticipated Results: Our understanding of the 4-D evolution of gradients known to occur in biological and physical parameters measured at the surface by satellites will be substantially improved by relating them to corresponding water-column data from the profiling array. Real-time satellite fields will provide an important data stream for the data assimilation effort. These products will also guide ship-sampling patterns, and be distributed to scientific partners and for public outreach.

TASK A6: Profiling Plankton Observatory in In-Situ Telemetering Array

Motivation: Gradients in biological and optical properties are often associated with physical fronts (Sinclair, 1988). Plankton communities respond to frontal physics in taxa-specific patterns. For example, plankton that migrate to the surface on a diel cycle can become concentrated in a near surface convergence at night and subsequently disperse during the day. In contrast, plankton that do not migrate may remain sparsely distributed regardless of the time of day and frontal processes. These mechanisms impact many critical environmental and regulatory issues, including episodic blooms of nuisance and toxic algae and planktonic food sources for commercially important fish species. To determine how frontal physics influence plankton distributions, we need quantitative taxa-specific observations of their distributions synoptically and at the same scales as observations of physical forcing properties.

Proposal: A suite of biological and optical parameters will be measured from a bottom-mounted profiling instrument platform that is located centrally in the in situ array (Figure 1c) and integrated with the acoustic telemetry network. These data will be relayed to shore in near real-time and will, together with the SeaWiFS ocean color, form the biological inputs to the coupled biological-physical modeling effort.

The AVPPO (Autonomous Vertically Profiling Plankton Observatory) collects high-resolution time-series data on the vertical position and taxonomic composition of plankton, together with a suite of optical variables, on vertical scales of millimeters to tens of meters. It has been developed by Dr. Scott Gallager (WHOI) and colleagues with support from NSF and ONR. Dr. Heidi Sosik (WHOI) designed its optical instrumentation, which was recently implemented for the CMO (Coastal Mixing and Optics) program (see Sosik et al. 1998). The profiler incorporates the following sensors: two CCD cameras (4 x 6 mm and 37 x 24 mm fields of view) with a strobe, a CTD, a fluorometer, downwelling and upwelling multi-spectral irradiance sensors, an AC-9 multi-channel transmissometer, a flowmeter, pitch and roll sensors, and an altimeter (Davis et al. 1992). The profiling body rests in a bottom-mounted cage containing a computer, batteries, and a winch. During a typical profile, the buoyant instrument platform is released from its cradle and floats passively to the surface. The level-winding winch and powered tensioner system then retrieves the package at a predetermined rate, typically 10 cm/s, while video and environmental data are recorded. (Examples of recent data from Georges Bank and Woods Hole Harbor are at seal.whoi.edu and limacina.whoi.edu.)

Use of AVPPO in FRONT will benefit from recent NSF funding to develop two additional features: a high resolution digital CCD camera with dynamic wavelet image compression and digital recording, and bi-directional data communications through RF and cellular telephone links. The first will facilitate real-time processing of plankton images to taxonomic group, and compression and storage of raw high-resolution video for periods exceeding 300 h or about 2400 profiles in 50 m depth. The second will provide the ability to transmit commands and receive data from the profiler each time it surfaces, through a dedicated RF link (AT&T WaveLAN at 2 mbits/second) and direct internet connectivity using PPP protocols by cellular telephone or Irridium satellite communication.

By inclusion of the AVPPO as a node in the subsurface acoustic communications network, FRONT will implement for the first time a fully interactive ocean observatory for biological and hydrographic data with information available in near real-time. NOPP funds are requested to acquire and integrate a Telesonar modem on AVPPO. This will allow a subset of its data to accompany the hydrographic and circulation data to shore via Coast Guard buoy gateway modems. The new AVVPO surface communication link could also serve as a auxiliary gateway node for the entire instrument array as may be needed should instrument failure or loss disable other paths to shore. Most importantly, a major advance in AVPPO capability is achieved by making a bi-directional and fully redundant acoustic communication pathway to shore available continuously, in addition to the shore links established when the profiler surfaces. This will allow the sampling scheme to be adapted, in real time, in response to intermittent events such as storms and passage of fronts. For example, AVPPO will initially conduct four profiles during each tidal cycle to resolve changes in hydrographic characteristics and plankton community structure at subtidal frequencies, but the package could be programmed to remain at a fixed depth to observe the evolution of properties when a front is passing.

We propose to deploy AVPPO for six months in year two and nine months in year three as an integrated part of the *in situ* profiling array. All deployments, retrievals and servicing cruises will be conducted from the R/V Connecticut. Based on previous experience, we anticipate servicing AVPPO at intervals of 6 to 8 weeks and for this we request support for 4 ship days in year two and 6 in year three. The following features are addressed during each service cruise: 1) sensors inspected and cleaned, 2) lead acid batteries replaced, 3) hardware inspected for wear and expendable items replaced such as lifting lines, hooks, compression and elastic items, worn cables, and 4) the complete set of raw and compressed video and hydrographic data downloaded.

Anticipated results: The AVPPO will collect long-term, high-frequency, near real-time vertical profile data on taxa-specific plankton distributions, optical properties, and hydrography. No other instrument can provide these data synoptically. Correlation length and time scales will be evaluated for hydrographic versus plankton community characteristics in the context of physical processes including occurrence of fronts. AVPPO optical instruments are configured to record at SeaWiFS wavelengths so as to facilitate improved understanding of 4D evolution of primary and secondary production through integrated analysis of profile data together with the extended surface coverage measured by satellite.

4.4 OBJECTIVE B: Evaluation of the Observation System

The capabilities of the observation system developed in Objective A will be evaluated by comparing fields to those obtained in a surface drifter deployment program and a series of rapid, high-resolution field surveys of hydrography, circulation, and microstructure. The surveys will combine a variety of state-of-the-art instrument systems with multiple-scale sampling methods. Information will be obtained about the system on scales of turbulent dissipation, on frontal scales, and on scales of tens of kilometers for comparison to situ instrument array data. Emphasis will be on measuring near-surface and near-bottom properties because these are areas that theoretical work on coastal ocean fronts suggests will have the strongest horizontal gradients in density, velocity and turbulent fluxes. We anticipate that this fieldwork will lead to improvements both in the development and the performance of the autonomous real-time observation system.

There are four major tasks: (1) the large domain circulation and hydrography survey, (2) the frontal-scale turbulence and mixing survey, (3) the frontal-scale circulation and hydrography survey, and (4) the Lagrangian surface current mapping program.

These field studies will be oriented around three ten-day cruises in each of the second and third years of the program, to be carried out while the observation system is operating. The first year will be devoted to acquiring, developing, and testing equipment and techniques during short cruises; this parallels the schedule for the development of the bottom-mounted instrument array and the CODAR system. During the ten-day cruises, the first and last three-day intervals will be devoted to describing the larger-scale fields and the middle interval will focus on the frontal areas as identified in near real-time by the integrated observation and data-assimilation system.

TASK B1. The Large Scale Surveys

Motivation. The principle role of the large-scale surveys is to provide sufficient information about the circulation and hydrography of the region to evaluate the ability of the new observation system to determine these fields. While a buoyant outflow from Block Island Sound around Montauk Point has been demonstrated by a short cruise that measured hydrography and made a drifter deployment (O'Donnell and Allen, 1996), little is known about the tidal, spring-neap, and seasonal variability in the region.

Proposal: The large-scale hydrography will be observed with an undulating vehicle, the URI Scanfish, towed by the R/V Connecticut. The Scanfish will be equipped with a Sea Bird Instruments SBE 911+ CTD, a dissolved oxygen sensor, and a Wetlabs fluorometer. Contemporaneously, the circulation will be observed by an RD Instruments 300 kHz Broadband ADCP mounted in the hull of the ship and interfaced to the differential GPS navigation system. The heading and tilt/roll information for the ship will be measured by the Trimble TANS Vector A-GPS (Attitude GPS) system presently being acquired and installed by UConn. This data will be used by the ADCP in order to determine the best possible estimate of water velocity. NOPP support is requested to upgrade an existing UConn RDI broadband ADCP to allow bottom tracking.

We expect observations to be made while the ship is steaming at 4 m/s, enabling the ship to survey 350 km per day. A radiator pattern will be surveyed 5 times each day. The along-track horizontal resolution of the survey will be approximately 100 m, as set by the ship speed and the ability of the Scanfish to profile up to 50-60 m depth in about 30 s. The ADCP data will be averaged over a similar scale. Averaging 100 pings every 100 s will result in a precision of a few cm/s. Since heading and pitch/roll data from the A-GPS system will be integrated with the ADCP deck unit, the results of every ping will be rotated to earth coordinates on deck and logged.

Dr. Dave Hebert (URI) will manage the installation and operation of the Scanfish and Dr. Jim O'Donnell (UConn) will coordinate the ADCP installation and observations. The effort will be staffed by UConn and URI technicians and graduate students and supervised by Hebert and O'Donnell. Both data sets will be archived and analyzed by O'Donnell and colleagues at UConn.

Anticipated results. The survey results will principally be used to evaluate the skill of the observing system. However, there is very little known about the outflow region of Long Island Sound and the fate of the seasonal buoyant effluent. These cruises will immediately yield new knowledge.

TASK B2. Frontal-Scale Turbulence Surveys

Motivation: The lack of observations of vertical mixing rates imposes a severe limitation on our understanding of frontal processes in coastal waters, as well as on the development of models for them. Typical comparisons are between observed and modeled distributions of scalar fields, which are known to be controlled by spatial variations in both mixing and advection processes. A necessary step toward isolating and understanding these mechanisms is to directly observe spatial and temporal variations in turbulent mixing in and near fronts. This data is needed to develop better parameterizations of microscale processes necessary to improve models for frontal behavior.

Proposal: Intensive surveys of turbulence properties in the area of fronts will be undertaken using two new microstructure instruments. New combinations of turbulence probes will be implemented that will improve our understanding of small-scale mixing processes. These measurements will be used to improve mixing parameterizations in the data-assimilative modeling component of the FRONT observation system.

The first microstructure instrument will be a newly configured REMUS AUV that incorporates additional sensors. Dr. Ed Levine (NUWC) will outfit it with 1) shear sensors to determine turbulent kinetic energy dissipation rates, 2) fast thermistors to determine thermal variance dissipation rates, and 3) an ADV-O (Acoustic Doppler Velocimeter) to determine the three components of velocity. By these means, direct measurements of both turbulent Reynolds stresses and turbulent heat fluxes are enabled. REMUS will also be equipped with two CTDs and upward- and downward-looking broadband ADCPs located within its body. These will provide measurements of stratification and shear and permit calculation of Richardson numbers on 2-m vertical scale. They will also facilitate direct comparison between co-located measurements of microstructure fields and larger-scale flow properties, as is critical to develop bulk representations of microscale processes.

The recently developed MicroSoar (Dillon et al., 1999; www.oce.orst.edu/po/research/microsoar) is the second new microstructure instrument, which will be implemented by Dr. Dave Hebert (URI). It uses a rugged capillary conductivity probe to resolve the thermal variance dissipation rate while it is towed at several knots. The MicroSoar, attached to the SeaSoar, was used during the ONR Coastal Mixing and Optics (CMO) project (Erofeev, 1998.). We will use the MicroSoar on a towed body with a Sea-Bird SVE 25 to map out the hydrographic and turbulent properties of frontal features observed during the larger scale surveys.

The MicroSoar and REMUS AUV measurements compliment each other. The AUV provides more independent measurements of turbulence, but it travels at a slower speed than the MicroSoar. The MicroSoar will provide a more rapid 3-D survey of the microstructure than the AUV. The AUV platform allows horizontal and vertical profiles of turbulent velocity measurements that are almost impossible from towed bodies. In contrast, turbulent temperature fluctuations can be measured from a towed body such as the MicroSoar. Having the AUV and ship in close proximity will allow turbulence data to be collected from two platforms. This will permit examination of the spatial and temporal correlation of mixing processes. The only previous study of this type was done in the equatorial Pacific using two ships several miles apart (Moum et al., 1994). A two-ship operation is not feasible for determining the horizontal correlation scales of mixing processes in the coastal ocean, especially at fronts. An AUV/ship operation provides a unique opportunity to resolve the appropriate scales.

Anticipated Results. New information will be collected about spatial and temporal variations in turbulent velocity and temperature fluctuations near and within coastal ocean fronts. Novel combinations of ship and AUV platforms will allow new intercomparisons. These measurements will provide important feedback to the observation system by allowing evaluation and improvement of subgrid-scale parameterizations of mixing processes in the data-assimilative modeling effort.

TASK B3. Frontal-Scale Circulation and Hydrography

Motivation. Recent investigations of coastal ocean fronts that have raised fundamental questions. The observations of O'Donnell et al (1998), for instance, have shown that the surface front at the edge of a buoyant river plume is quite clearly a region of surface convergence (the currents on either side move towards the front). This result is in many ways consistent with the model of Garvine (1974). In contrast, the model of the formation of a coastal current developed by Chapman and Lentz (1994), predicts that the front at the offshore edge of the coastal current should be a convergent in the bottom boundary layer and divergent at the surface. These contrasting predictions have important ecological implications. It is therefore time to examine in detail the structure of the hydrography and circulation in the vicinity of an estuary outflow where both types of fronts may expected be found. The FRONT demonstration site is ideal for such a study.

Towed vehicles like the Scanfish now allow almost continuous underway sampling, and we estimated a horizontal resolution of order 100 m in the large scale survey described above. However, these systems have limitations when operating near the surface and the bottom. At shallow depths they may be influenced by the wake of the towing vessel. Bottom front observations are even more difficult because limits to navigational control when deeper than 100 m make it hazardous to tow-yo near the bottom with sensitive instruments. There is a clear need for techniques to measure hydrographic properties in boundary layers at intervals of order 1-10 m.

Proposal: We propose to develop a novel system for frontal surveys that uses a towed depressor fin with a CTD chain and a combination of hull-mounted and towed ADCPs. The depressor fin will be towed at approximately 10-15 m below the surface, following the design of Marmorino and Trump (1994). Five CTD sensors will be attached, at approximately two-meter intervals, to a cable connected between the depressor and a surface float. Hydrographic data will be sampled at 1 Hz and displayed on the ship in real time. This approach has been demonstrated successfully in observations of small scale fronts on the outer shelf near Cape Hatteras (Marmorino and Trump, 1994).

To observe the circulation shallower than four meters, which is inaccessible to the hull-mounted ADCP, we will employ a second towed vehicle. It is a floating cylinder with a 1200 kHz broadband ADCP mounted in a 1 m long keel just below a CTD, modeled on the design Trump et al. (1995) termed TOAD. This system has been effective in observing a range of frontal structures (O'Donnell et al. 1998). The 1200 kHz ADCP will not be able to bottom track in water depths greater than 30 m, so we will employ reference layer processing and use the data from the hull-mounted ADCP to specify the reference layer velocity. The results of every ping will be logged for post processing. The two packages, depressor and cylinder, will be simultaneously towed from the ship.

In the first year of the program we will acquire, fabricate, and test the necessary new equipment systems. The 1200 kHz ADCP and CTD are available for the project. NOPP support is require to acquire and assemble the hydrographic array from five Ocean Sensors CTDs, a depressor fin, cabling and a data acquisition computer. Four days of ship time will be required for testing. During the second and third years of the program we will deploy these systems to observe the structure of the fronts seen in the large-scale surveys and the data-assimilative model predictions. This will require 3 days of ship time during four of the survey periods, for a total of 12 days. Dr. Jim O'Donnell (UConn) will be responsible for development of the new equipment, conducting of the field observations, and analysis of the data. NOPP support is requested for a graduate student at 50% and a technician at 25% in each year of the program.

Anticipated Results: The new measurement technique will provide near-synoptic observations of the small-scale hydrographic and current structure of surface fronts in the survey domain. These will enable the evaluation of the FRONT observation system that uses sparse array data and modeled dynamics. O'Donnell and Bogden (UConn) will collaborate on this evaluation. In addition, the frontal observations will immediately be of interest since they will be the first of their kind.

TASK B4: Surface drifter program

Motivation. One key test of the observation system in Objective A is to assess its ability to determine the trajectories of drifting targets. This capability is of broad interest, but particularly relevant to managers of Coast Guard search and rescue and oil spill response operations. The USCG Research and Development Center has been developing the technology for deploying CODE-style (Davis, 1985) drifters from aircraft and helicopters, and assessing their performance (Allen, 1996). Coordinating a drifter program with the FRONT observation system will not only serve as a means for its evaluation, but will also provide a unique opportunity to further advance drifter technologies. In addition, the broad surface coverage gained from drifter deployments is uniquely able to facilitate comparisons, in the manner of Graber et al (1997), between independent in situ measurements and CODAR data, and to test and improve CODAR algorithms (Task A4 above).

Proposal. We propose to track aircraft-deployed drifters during the ten-day cruises for FRONT objective B. At the start of the field survey, USCG will air-deploy ten GPS-tracked drifters that will transmit their positions via ARGOS. The initial deployment positions will be within coverage of the CODAR system. Drifters that fail to operate after splashdown will be recovered by an attending USCG or UConn vessel. After repair, if possible, the drifter will be deployed from ship. During the subsequent week the USCG will monitor drifter positions, and the R/V Connecticut or a vessel from USCG Stations New London or Moriches will recover those that appear to be leaving the study area. Such drifters will then be redeployed within the study area.

The USCG will provide funds for purchase of air-deployed drifters. Expenses and staff time associated with aircraft and ship operations, recovery, refurbishment, and data archival will also be borne by the USCG. Drs. Dick-O'Donnell and Herring (both of USCG) will be responsible for the deployments and archival of ARGOS reports. O'Donnell of UConn will produce velocities for comparison with CODAR.

Anticipated results. The drifter program will provide two significant contributions to the system evaluation. The first will be to allow assessment of the surface currents determined by data assimilation by providing independent Lagrangian trajectory data. The second is in helping evaluate the CODAR algorithms as described above in Task A4. While it is acknowledged that care must be taken in comparing Lagrangian and Eulerian velocities, the broad spatial coverage of the drifters provides invaluable new information without requiring additional ship expense.

4.5 OBJECTIVE C: Education and public outreach

Education: A valuable resource from FRONT is real-world data in real- time, which enables classroom applications with a relevant context. Ivar Babb (NURC-UConn) will rely on two educational allies who have experience developing educational programming and have previous NOPP educational funding. The Rutgers University Institute of Marine and Coastal Sciences (IMCS) is coordinating internet-based approaches to using continuous real-time data streams (De Luca et al, 1997). IMCS personnel have been contacted (J. McDonnell, personal comm.) and will assist us in adapting teaching modules for use with FRONT research products; their availability will be advertised through local networks of marine educators.

Our second educational partner is the Jason Foundation, an enrichment program designed to excite students about science through advanced telecommunication and internet links. Jason impacts over half a million students each year. Its goal to establish permanently accessible, ocean-oriented, interactive internet and curricular resources has received major support previously from NOPP. Jason project personnel will assist us in developing new teaching modules based on FRONT. One means for their distribution will be links under the permanently available teaching resources on the popular Jason website.

Outreach: A principle goal will be interaction with the local commercial fishing industry, particularly those that could severely impact the bottom-mounted instrument array. The president of the Southern New England Fisherman and Lobsterman Association, Arthur Madeiros, has agreed to assist in coordinating a meeting with trawlers and scallop draggers that fish in the area of the FRONT array site. The intent of the meeting is to explain the objectives of FRONT and help generate community awareness and support. In addition, during year one, fishermen will drag across the prototype trawl-resistant instrument mounts, and the results of these critical tests will be incorporated in a redesign.

Mystic Aquarium (MA) is a division of Sea Research Foundation, Inc., a non-profit institution located in Mystic, CT dedicated to education and research. Following a recent $52M expansion program, to conclude in Spring 1999, the newly renovated MA exhibits are to be organized around the concept of ecological "hotspots" where growth is unusually strong. This idea dovetails with the frontal boundaries that are the focus of FRONT. We propose to implement a FRONT display integrated with the existing MA collection of live exhibits, sound programs, interpretive graphics, and docents. It will employ graphics, computer terminals, and video monitors to present information in a near real-time format. Preliminary displays, that will present the EPA-sponsored Long Island Sound EMPACT project, will be expanded to include FRONT products as they are made available. We anticipate capitalizing on this opportunity to reach the more than one million projected visitors to MA per year.

4.5 References

Adcroft, A.J., Hill, C.N. and J. Marshall, 1997. Representation of topography by shaved cells in a height coordinate ocean model Mon. Weather Rev., 125, 2293-2315

Allen, A.A., 1996. The performance of GPS/ARGOS self locating datum marker buoys (SLDMBs). OCEANS96 MTS/IEEE Conference Proceedings, pp 857-861.

Barrick, D. E., M. W. Evans, and B. L. Weber, 1977. Ocean surface currents mapped by radar. Science, 198, 138-144.

Bennett A.F., 1992. Inverse Methods in Physical Oceanography. Cambridge University Press, Cambridge, 346 pp. 1992.

Bogden, P. S., P. Malanotte-Rizzoli, and R. Signell, 1996. Open-ocean boundary conditions from interior data: Local and remote forcing of Massachusetts Bay. *J. Geophys. Res.* 101(C3), 6487-6500.

Bogden, P.S. and J. O'Donnell, 1998. Generalized Inverse analysis of current measurements from a moving ship: estimating the tidal and non-tidal flows in Long Island Sound. J. Marine Res. 56, 995-1027.

Bretherton, F. P., R. E. Davis, and C. B. Fandry. 1976. A technique for objective analysis and design of oceanographic experiments applied to MODE-73. Deep Sea Res. 23, 559-582.

Cayula, J. F. and P. Cornillon. 1995. Multi-image edge detection for SST images. Journal of Atmospheric and Oceanic Technology. 12: 821-829.

Chan, C. and J.A. Yoder, 1999. A comparison of surface temperature and chlorophyll frontal boundaries in northwestern Atlantic shelf and slope seas. (submitted to Marine Ecology Progress Series).

Chapman, D.C. and S.J. Lentz, 1994. Trapping of a coastal front by the bottom boundary layer. J. Phys. Oceanogr. 24, 1464-1479.

Cushing, D.H. 1975. Marine ecology and fisheries. Cambridge University Press, Oxford

Davis, C.S., S.M. Gallager, M.S. Burman, L.R. Haury and J.R. Strickler. 1992. The video plankton recorder (VPR): design and initial results. Archiv ffur Hydrobiologie, Beihefte, Ergebnisse der Limnolohie, 36:76-81

Davis, R.E., 1985. Drifter observations of coastal currents during CODE: the method and descriptive view. J. Geophys. Res. 90, 4756-4772.

De Luca, M., et al. 1997. Bringing the ocean into the precollege classroom through field investigations at a national underwater laboratory. Proposal to the National Ocean Partnership Program.

Denman and Gargett, 1995. Biological-physical interactions in the upper ocean: the role of vertical and small scale transport processes. Ann. Rev. Fluid Mech 27:225-255

Dillon, T.M., J.A. Barth, Y.A. Erofeev, and G.H. May, 1999. Microsoar: A new instrument for measuring microscale turbulence from rapidly moving submerged platforms, J. Atmos. Oceanic Tech. (submitted).

Dupouy, C., J.P. Rebert and D. Toure. 1986. Nimbus-7 coastal zone color scanner pictures of phytoplankton growth on an upwelling front in Senegal. In: Marine Interfaces Ecohydrodynamics. J.C.J. Nihoul (Ed.), Elsevier Science Pub., pp. 619-644.

Erofeev, A.Y., T.M. Dillon, and J.A. Barth, 1998. Microstructure measurements in the Middle Atlantic Bight, EOS, Transactions of the American Geophysical Union, 79(1), supplement, OS145.

Follows, M. and J. Marshall, 1999. Modulation of biogeochemical cycles by the North Atlantic Oscillation. Submitted to *Deep-Sea Res.*

Follows, M., R. G. Williams, J. C. Marshall, 1996. The solubility pump of carbon in the subtropical gyre of the North Atlantic. J. Mar. Res. 54. 605-630.

Gallager, S.M, C.S Davis, A.W. Epstein, A. Solow, R.C. Beardsley. 1996. High Resolution observations of plankton spatial distributions correlated with hydrography in the Great South Channel, Georges Bank. Deep Sea Research II 43:1627-1664

Garvine, R.W. 1974. Physical features of the Connecticut river outflow during high discharge. *J. Geophys. Res.* 79 831-846.

Graber, H.C., B.K. Haus, R.D. Chapman, and L.K. Shay, 1997. HF RADAR comparisons with moored estimates of current speed and direction: expected differences and explanations. J. Geophys. Res. 102, 18749-18766

Hooker, S.B., C.R. McClain and A. Holmes. Ocean color imaging: CZCS to SeaWiFS. 1993. MTS Journal, 27: 3-15.

Large, W. G., J. C. McWilliams, S. C. Doney, 1994. Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parameterization. Reviews of Geophysics. 34. 363-403.

Lee, T., and J. Marotske, 1998. Seasonal cycles of meridional overturning and heat transport of the Indian Ocean. J. Phys. Ocean. 28. 923-43.

Legg, S. and C. Wunsch (1999) ``Mixing generated by internal waves interacting with rough topography," Proceedings of the 10th Aha Huliko'a Hawaiian Winter Workshop.

Linden, P.F. and J. E. Simpson, 1988. Modulated mixing and frontogenesis in shallow seas and estuaries. Cont. Shelf Res. 8, 1107-1127.

Lipa, B. J., and D. E. Barrick, 1983. "Least-squares methods for the extraction of surface currents from CODAR crossed-loop data: Application at Arsloe". IEEE J. Ocean. Engr., OE-8, 226-253.

Marmorino, G.O. and C.L. Trump, 1996. High resolution measurements made across a tidal intrusion front. J. Geophys. Res. 101, 25661-25674

Marmorino, G.O. and C.L. Trump, 1994. A salinity front and current front near Cape Hatteras, north Carolina. J. geophys. Res. 99, 7627-7637.

Marshall, J., C. Hill, L. Perelman, and A. Adcroft, (1997a) Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling, J. Geophysical Res., 102(C3), 5733-5752.
Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey, (1997b) A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers, J. Geophysical Res., 102(C3), 5753-5766.
McClain, C.R., M.L. Cleave, G.C. Feldman, W.W. Gregg, S.B. Hooker and N. Kuring. Science quality SeaWiFS data for global biosphere research. 1998. Sea Technology, Sept. 1998: 10-16.
Moum, J.N., M.C. Gregg, R.C. Lien and M.E., 1994. Carr Comparison of turbulent kinetic energy dissipation rates from two ocean microstructure profilers. J. Atmos. Ocean Tech., 12, 346-366, 1994
Nihoul, J.C.J. (Ed.). Marine Interfaces Ecohydrodynamics. 1986. Elsevier Science Pub., 670 pp.
O'Donnell, J. 1990. The formation and fate of a river plume; A numerical model. J. Phys. Oceanogr. 20, 551-569.
O'Donnell, J. 1993. Surface Fronts in Estuaries: A Review. Estuaries, v16, 1, 12-39.
O'Donnell, J. 1997. Observations of near surface currents and hydrography in the Connecticut River plume with the SCUD array. J. Geophys. Res. 102, 25021-25033.
O'Donnell, J., and A. Allen, 1992. Observations of the hydrography and Lagrangian surface drift in Block Island Sound. Proceedings of the First Long Island Sound Research Conference, New Haven, Connecticut. October 23-24, 1992
O'Donnell, J., G.O. Marmorino and C.L. Trump, 1998. Convergence and downwelling at a river plume front. J. Phys. Oceanogr. 28, 1481-1495
Sinclair, M. 1988. Marine populations: an essay on population regulation and speciation, Department of Fisheries and Oceans, Canada 252 pp.
Sosik, H. M., R. E. Green and R. J. Olson. 1998. Optical variability in coastal waters of the Northwest Atlantic. In: Ocean Optics XIV, S. G. Ackleson (ed.).14 pp.
Sournia, A. Pelagic biogeography and fronts. 1994. Prog. Oceanog. 34: 109-120.
Stammer, D., C. Wunsch 1994. Preliminary assessment of the accuracy and precision of TOPEX/POSEIDON altimeter data with respect to the large-scale ocean circulation. J. Geophys. Res. 99, 24584-24604.
Trump, C.L., G.O. Marmarino, and J. O'Donnell. 1995. Broadband ADCP Measurements of the Connecticut River Plume Front. Proc. of the Fifth IEEE Working Conference on Current Measurement. pp 73-78 St. Petersburg, FL. February 7-9, 1995.
Ullman, D. S. and P. C. Cornillon. 1999. Surface temperature fronts off the east coast of North America from AVHRR imagery. (submitted to Journal of Geophysical Research).
Ullman, D. S., P. C. Cornillon, and T. P. Mavor. 1999. SST fronts in winter off the east coast of North America. In "Oceanic Fronts and Related Phenomena", UNESCO Intergovernmental Oceanographic Commission Workshop Report. (in press).

5. Capabilities, related experience, and facilities.

The R/V Connecticut, a newly designed and built 76-foot research vessel operated by the University of Connecticut Marine Sciences and Technology Center (MSTC), will be used in the survey and mooring operations. It is equipped with an A-frame, winch and crane and is ideal for mooring and ROV operations. UConn faculty and MSTC staff have extensive experience with instrument arrays. A recently funded EPA project (PI: Bohlen) is acquiring and distributing real-time data from bottom-mounted ADCPs in Long Island Sound. Existing UConn computer systems will serve all data products over the internet for FRONT.

The URI remote-sensing group has developed extensive resources for analysis and presentation of satellite data with prior NASA and NOAA funding. They have supported many other large projects with near real-time satellite images for planning field sampling. The URI small-scale mixing group has considerable experience with microstructure equipment and analysis of turbulence data, with fieldwork in environments as diverse as shallow New England estuaries and the equatorial Pacific. This, together with previous experience with a towed vehicle, Seasoar, will directly benefit the proposed operations.

Woods Hole Oceanographic Institution is uniquely suited for the plankton observatory technology development, with engineering expertise in ocean sensor communication with shore-based laboratories.