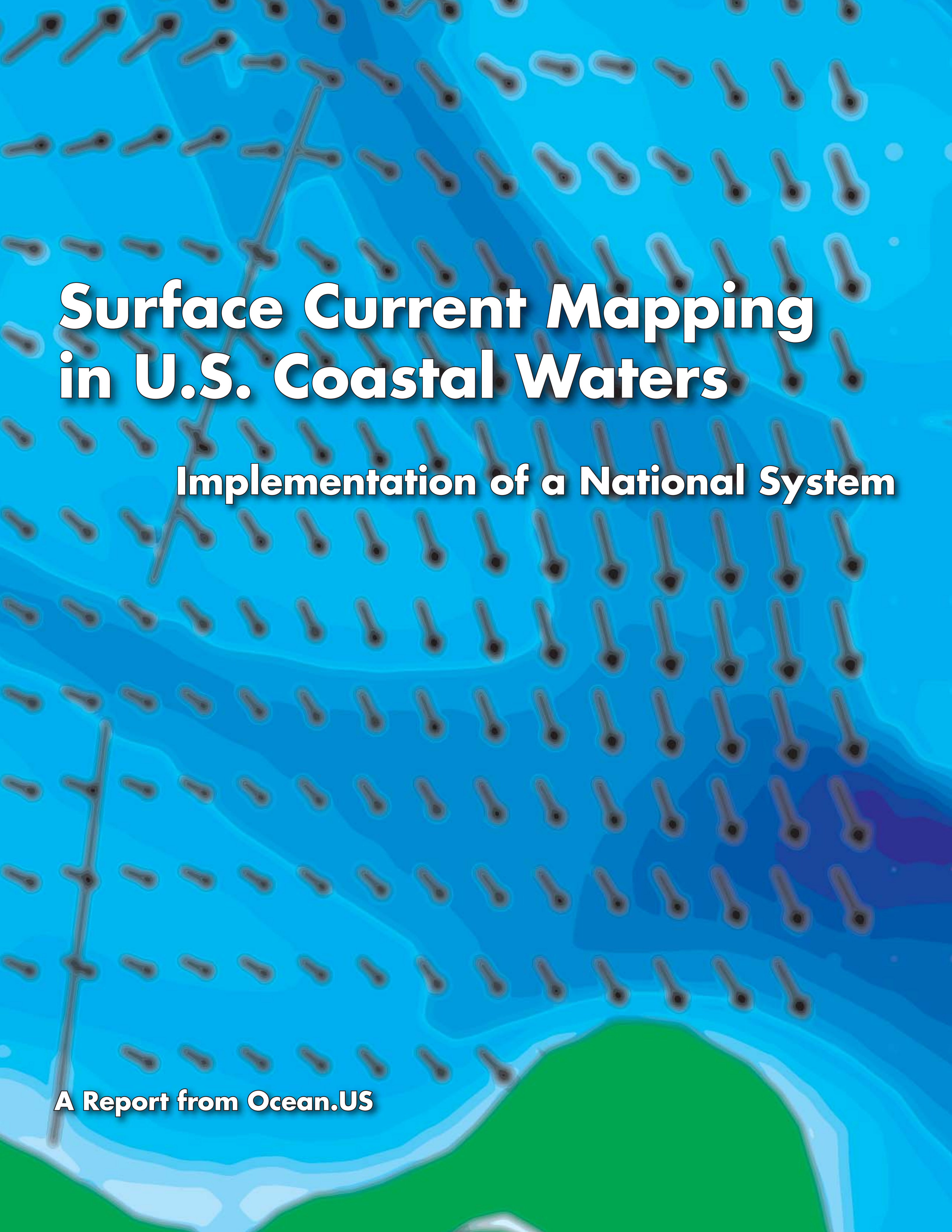
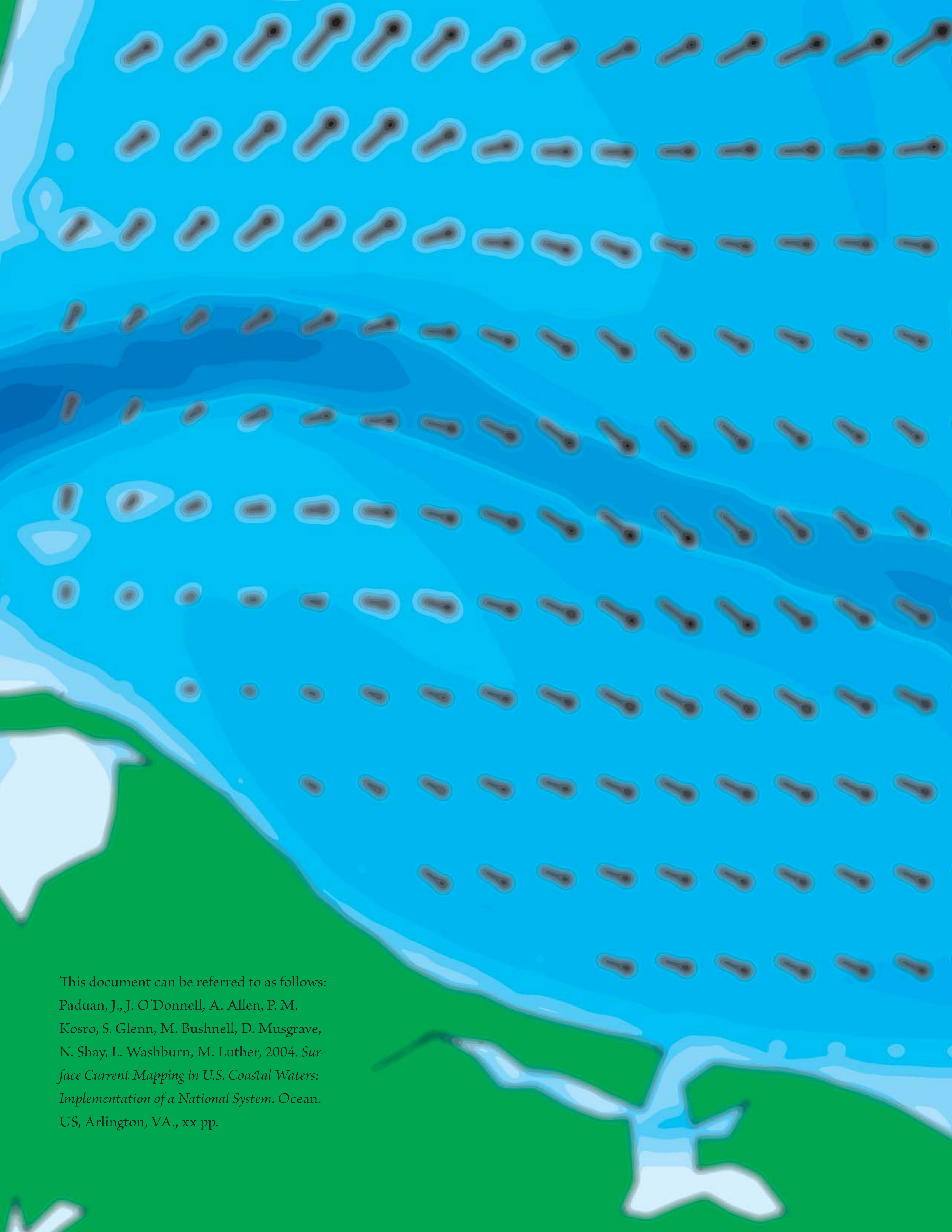


Surface Current Mapping in U.S. Coastal Waters

Implementation of a National System

A Report from Ocean.US



This document can be referred to as follows: Paduan, J., J. O'Donnell, A. Allen, P. M. Kosro, S. Glenn, M. Bushnell, D. Musgrave, N. Shay, L. Washburn, M. Luther, 2004. *Surface Current Mapping in U.S. Coastal Waters: Implementation of a National System.* Ocean. US, Arlington, VA., xx pp.

Surface Current Mapping in U.S. Coastal Waters

Implementation of a National System

A Report from Ocean.US

Report prepared by the Surface Current Mapping Steering Committee
in Coordination with the National Office for Integrated and Sustained Ocean Observations (Ocean.US)

June 2004

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Executive Summary

In September 2003, Ocean.US established the Surface Current Mapping Initiative (SCMI). Surface current mapping is very important to the Integrated Ocean Observing System (IOOS), and the availability and maturity of High-Frequency (HF) radar technology makes reliable surface current mapping now possible. Ocean.US appointed an SCMI steering committee to address critical technical issues associated with implementation of a surface current mapping system for coastal U.S. waters. Committee membership included people experienced with existing, research-based HF radar networks, operational installations, users needs, and federal agency requirements. Users and federal agency representatives were also included. Issues identified by the steering committee included governance of an integrated current mapping network, siting HF Radars, coordination of frequency allocations, development of HF Radar products, research topics, and vessel tracking. It is anticipated that the cost for a nation-wide SCM network will be about $15 M to $44 M for 100 to 200 sites and that the annual operating cost will be about $5.3 M to $13.5 M. The range in cost depends on the coverage in Alaska, Hawaii, and the trust territories and variability in installation and maintenance costs. The committee recommended pilot projects that would lead to operational systems.

Background

Surface currents measurements in the U.S. Exclusive Economic Zone (EEZ) have been repeatedly identified as critical for meeting many Integrated and Sustained Ocean Observing System (IOOS) and Ocean Research Interactive Observatory Networks (ORION) goals. These currents can be mapped with a radio frequency technique called, variously, HF Surface Wave Radar, surface current radar, or CODAR (Coastal Ocean Dynamics Applications Radar, the dominant commercial system). For purposes of this report, we will be referring to it as surface current mapping or SCM. The CODAR system or other commercially available products will be used in any SCM implementation. The Ocean Research Advisory Panel (ORAP), which provides scientific advice to the National Oceanographic Research Leadership Council (NORLC), recently endorsed the establishment of such as system as did the community-wide workshops convened by Ocean.US, the Coastal Ocean Processes (CoOP) project office, and the Consortium for Oceanographic Research and Education (CORE).

In light of the importance of SCM, and the availability of cost-effective HF radar technology, Ocean.US established the Surface Current Mapping Initiative (SCMI) in September 2003. At this early stage, the SCMI consists of a planning effort to design the framework for a national system to measure surface currents in coastal waters. Ocean.US asked the SCMI Steering Committee to consider critical technical issues, governance models, and costs. Committee membership includes people experienced existing, research-based HF radar networks, operational installations, users needs, and federal agency requirements. Users and federal agency representatives were also included.

SCM networks currently require transmit and receive antennae at each site. Direction-finding instruments have a small number of antennae placed several tens of meters apart that can "look" in both directions along a beach. Phased-array designs use more widely spaced antennae (~100 m) and look in one direction along a beach. Ideal locations for both types of systems are just shoreward of open beaches. Because of the compact footprint, direction-finding systems are also convenient to deploy on headlands or in heavily populated areas where space is a premium. The basic measurements provided by all systems are maps of radial currents: the speed of the surface water towards or away from the antennae. Vector currents are available for the region of overlapping coverage from two or more individual sites. Complete coverage of a typical coastline requires antennae sites spaced about every 100 km along the coast, assuming offshore ranges of 100-180 km (Figure 1).

There are over forty individual SCM systems presently operating in U.S. EEZ waters. All but a few are operated by research institutions. Many are long-range (100-180 km) while others are more regional-scale (30-60 km), higher-resolution systems. Examples from of the types of products available from these systems are provided in Appendix I.

SCMI is breaking new ground on how the IOOS can create new observing systems and transition them from research projects to operational systems. Having academic and federal agency representatives at the same table has proven to be a very effective way to identify and address critical issues.

The bulk of the SCMI Steering Committee's work was done while meeting on September 11, 2003 at Ocean.US offices in Clarendon, Virginia. Later in the fall and winter, informal meetings were held at other locations. In March 2004, the Steering Committee held its final meeting under sponsorship of the Alliance for Coastal Technologies (ACT) the University of South Florida. The report from the ACT-sponsored meeting will be available separately.

Ocean. US asked the committee to identify the critical issues affecting implementation of a national SCM system. The following pages contain short descriptions

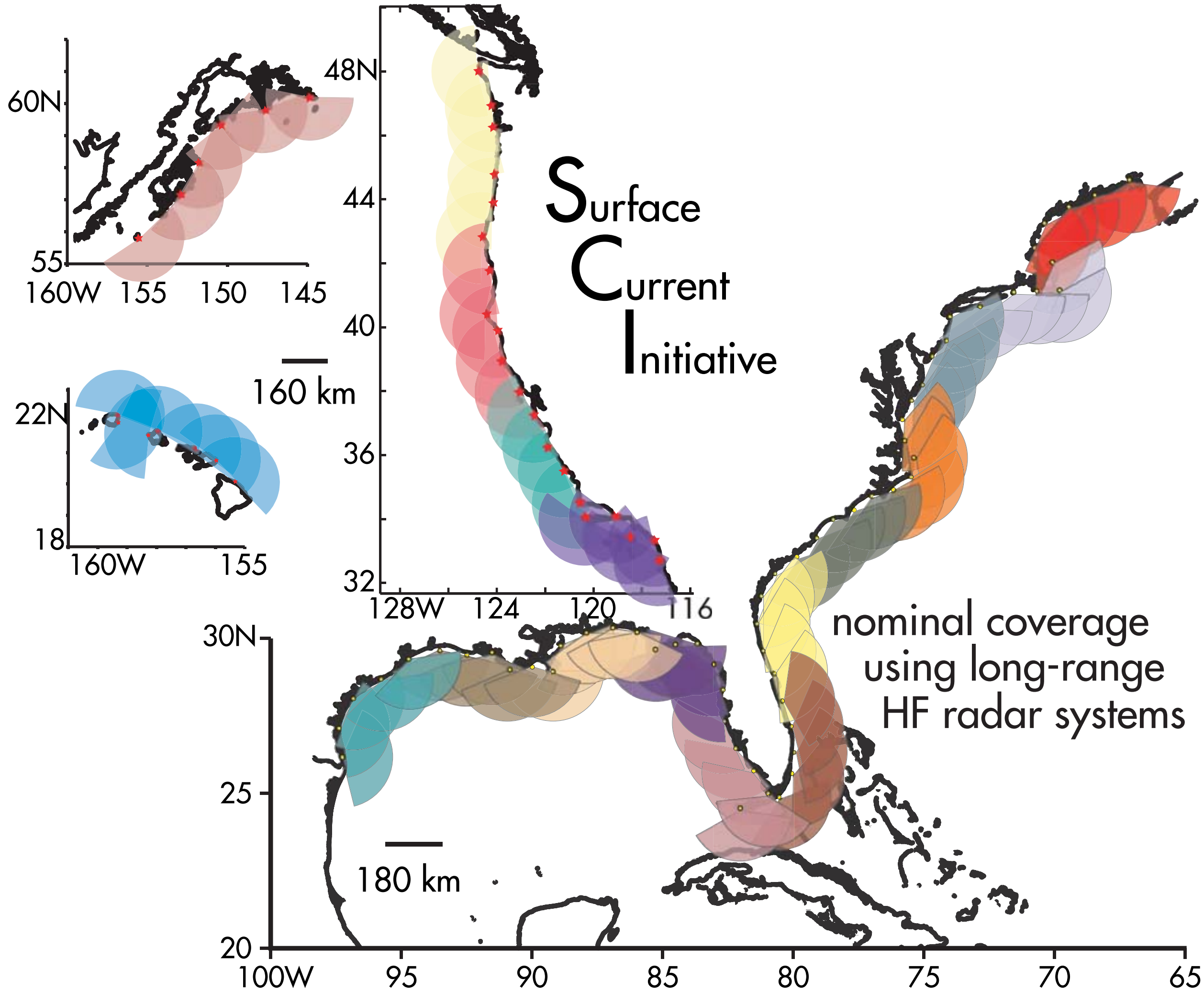


Figure 1. Surface current mapping coverage from a 93-site, long-range HF radar network. Color coding is intended to illustrate the nominal distribution of local SCM operating "nodes." The networks in Hawaii, Alaska, and other U.S. territories require continuing assessment. The coverage depicted here for those regions is for example only.

of topics recommended by the SCMI Steering Committee for immediate action or high-priority, continuing attention. Other topics will certainly be introduced in the future by the expanding user community and governing boards, but these are known to be important based on the experiences of the many system operators that have provided input to the steering committee.

Critical Issues

The SCMI steering committee identified six critical issues relevant to implementation of a national SCM system.

1. Governance of an Integrated Surface Current Mapping Network

Description

The SCMI Steering Committee recommends establishment of a national organization to promote and oversee a backbone network of surface current mapping systems that provide surface current observations. The SCM systems' horizontal resolution, overall coverage, funding pathways, and implementation phasing priorities will be determined by obtaining community feedback.

Currently, SCM system networks are operated by university research groups. In the next phase of development, expansion of these networks is likely to occur under the auspices of IOOS Regional Associations. It will be beneficial to include a nationwide, coordinating body at the earliest stage.

The coordination and optimal use of a spatially broad network of SCM systems will benefit from a common governance structure. This is particularly true because the SCM system, by definition, will be spread across regions and across institutional types, including federal government laboratories, state government offices, and academic institutions. The proposed governance structure will draw from each of these institutional components to provide a single governing board.

The governing board for SCM data coordination will oversee standard product specifications, data exchange formats, and error characterization standards required for the common data backbone. They will recommend algorithm standards and upgrades based on research results as they become available. The same SCM data will also be available to local operators and regional observing systems, which may have additional products tailored to the region.

The governing board will also recommend and oversee the personnel structure and make up for backbone network operations.

Actions Needed

- Establish a nationwide coordination body for SCM system implementation.
- Canvas regional SCM system operators and the science community for nominations for governing board members.
- Include the governance model in all stages of formal planning for a spatially broad network of SCM systems.
- Codify interagency aspects related to personnel supervision.
- Establish a software sharing and IOOS/DMAC interface subcommittee.

Potential Experts

SCMI Steering Committee members, agency representatives.

2. Siting of HF Radars

Description

Implementation of national and regional systems of HF radar depends on finding and gaining access to suitable sites. The permitting process may involve multiple governmental agencies at the federal, state, and local levels including (but not limited to): the U.S. Coast Guard; National Park Service; Federal Aviation Administration; National Oceanic and Atmospheric Administration; Bureau of Land Management; U.S. Navy; U.S. Air Force; U.S. Army, Army Corps of Engineers; analogous state, city, county agencies, native entities; and private individuals, corporations, and nongovernmental organizations (e.g., Nature Conservancy). Data products from the national and regional HF radar systems will benefit many of the same agencies from which permits will be required. However, the utility of these products to these agencies may not be obvious now.

Existing constraints on siting HF radar systems eliminate many areas of coastline due to geographical properties such as distance from shore, topography, and coastal shape.

Autonomous systems with remote power and data transfer will be needed at many sites, for example, islands and remote headlands. In addition, autonomous portable systems for emergency response will be needed. Operational aspects of remote sites may require leveraging logistical resources to maintain these sites.

The visual impacts of the antenna and ancillary equipment (e.g., solar cells, generators) may be a cause for denying or delaying permits.

Actions Needed

- Inform permitting agencies of the benefits of HF radar for their particular agency mission.
- Compile lists on the Web of existing and potential sites.
- Develop methods to prevent vandalism or damage by large animals.
- Develop options (e.g., rental agreements, easements) for use of private property.
- Develop minimal physical and electromagnetic requirements for siting HF radar and develop new technology for dealing with difficult configurations.
- Streamline the permit process. One approach could be through a system-wide permitting office.
- Develop methods for power generation and data transmission for remote and portable systems. These may include wind, solar, fuel cell, and fossil fuel generators.
- Develop lower power HF radar systems.
- Develop cooperative agreements for logistical support of remote systems.
- Designate HF radar as an aid to navigation.
- Decrease the impacts of antenna and ancillary systems.
- Prioritize various data transmission methods.
- Develop remote communications and power working group.

Potential Experts

Agency land-use personnel and agency heads, existing system operators.

3. Coordination of Frequency Allocations

Description

The frequency band useful for SCM operations is constrained by oceanic wavelengths. As the number of oceanographic SCM systems increases there will be increasing competition for frequency allocations in the limited part of the electromagnetic spectrum available for these observations. Competition will be increased between SCM systems and other users of the HF band.

SCM signals can travel great distances. Therefore, it is not uncommon for signals from one system to produce detrimental noise at the receiver of another system operating at or near the same frequency. Hardware solutions must be sought that allow several SCM systems to share exactly the same operating frequency through, for example, GPS-based precise timing.

Today, all SCM system users are given frequency allocations that are called "secondary" or "not-to-interfere" licenses. This license means that if any primary user operating in the band (or influenced by operations in the band) complains, the SCM system operator must immediately shut down or shift frequencies.

Actions Needed

- Increase use of GPS precise time and other techniques to allow multiple SCM installations to share a given frequency allocation.
- Establish an action committee, including multiple federal and international partners, to generate formal requests to the Federal Communications Commission (FCC) and its international counterpart, the Interdepartment Radio Advisory Committee (IRAC), for the creation of dedicated SCM system frequency and power allocations within the HF band.

- Contact officials within the National Weather Service (NWS) to seek advice based on recent successful experiences obtaining dedicated frequency allocations for NexRAD (Next Generation Radar) weather radar systems.
- Disseminate instructions for obtaining secondary licenses from the FCC and IRAC to all SCM system users; insure that all users are aware of the requirements for legal operations with respect to frequency allocations.
- Conduct frequency surveys at SCM system sites to establish frequencies to be requested. Consider obtaining professional assistance for this effort, both legal and radio frequency (RF).

Potential Experts

Instrument manufacturers, FCC representatives, NWS radar operators, amateur radio representatives.

4. Development of HF Radar Products

Description

HF radar systems are capable of generating several different products. The primary HF radar system products are either measurements of the surface current fields or the detection of ocean-going vessels. Single-point wave-height measurements are a secondary product of those systems presently dedicated to SCM.

The uncertainties in measurements of surface currents and waves will require further investigation (see Research Topics in item 5 below for further description). Further work is also required to mature vessel detection and tracking capabilities of HF radar systems; these are discussed under Vessel Tracking in item 6 below.

Available products vary in format and are not yet provided through a central location. Expanded products should be developed in coordination with users.

Actions Needed

- Establish formats for sharing/comparing across regions and systems.
- Establish a product-developers' working group, to augment development of shared standard analysis and display software.
- Involve users/stakeholders in product development.
- Identify locations for central quality control, archiving, and product distribution.

Potential Experts

Present system operators, operational Coast Guard and hazardous material (HAZMAT) responders, CoOP steering committee members.

5. Research Topics

Description

Products from SCM systems derive from the intrinsic capabilities of the hardware and from ever-improving algorithms (software). Improvement of the accuracy and the characterization of the system performance must be ongoing activities. Key topical areas include:

- Better understanding of radial current observations and uncertainties.
  - > Define uncertainties in radial currents and their dependence on range, azimuth, and signal-to-noise ratio for both direction finding and beam forming applications.
  - > Improve the blending of surface currents from systems of differing frequencies and footprints to form a best current estimate.
- Better understanding of how to assimilate surface currents into models.
  - > Determine temporal and spatial correlations of the errors and uncertainties for both direction finding and beam forming applications.
- Research and development of additional environmental products beyond surface currents.
  - > Continue development of the use of radar backscattered signals to determine the wave and wind fields.
  - > Exploit the approach of using multiple frequencies to determine near-surface shear.
- Research and development of expanded SCM instrumentation and algorithms.
  - > Assessment of the impact of changing the number of antennae in phased array systems (i.e., 12 versus 16 antennae?), which is central to siting issues.
  - > Continue development of a superdirective compact antenna array.

> Develop compact transmitters for offshore buoy deployments to improve coverage offshore and nearshore.
> Develop receivers that can work on moving ships.
> Research and develop multistatic geometries and processing algorithms for even better vector-mapping coverage.

- Research and develop Lagrangian applications and interpretations.

Actions Needed

- Support collaborations among various radar groups, research associations, and modeling communities.
- Coordinate the development and distribution of improved algorithms for surface current and wave estimation.

Potential Experts

SCM steering committee members, system operators, signal processing specialists from other engineering disciplines.

6. Vessel Tracking

Description

HF Radar systems are also capable of tracking surface vessels. Single-look, large-phased arrays have been operated for ship-tracking purposes for ten years off the east coast of Canada where they are used to look for large vessels on steady courses in a low-density traffic area. Recent testing of these systems in a high-traffic region in the presence of strong current shear has shown difficulties tracking smaller targets of interest.

Compact, multi-look, direction-finding systems are being tested in single-ship research applications using existing hardware for monitoring surface current fields. Currently, individual cross-spectra are saved and vessel peaks can be identified for vessels with radial speed components outside of the Bragg peaks. Vessel-detection capabilities from individual sites can be increased by modifications to the waveform and duty cycles that increase the energy in the nearshore range bins at a slight cost of a reduction in range for current monitoring. Vessel peaks identified in the spectra and run through the direction-finding algorithm produce detection files of range rate, range, and direction. Real-time vessel tracking poses a significant data transfer and communication problem because large data sets need to be shared between remote systems several times per minute.

Actions Needed

- To take advantage of the dual use capabilities, continue development of ship-tracking capabilities in multi-static networks of HF radars.
- Develop and test additional detection algorithms-
  a) Peak Picking for vessels outside the Bragg peak
  b) SIFTER – potential to pull vessels out of Bragg peak
  c) MUSIC applications to vessels and dependence on signal to noise.
- Develop detection and associated software for a multi-ship environment.
- Develop Kalman Filter feedback – track before detect.
- Develop a multi-static vessel-tracking capability that uses a single receiver to listen in on multiple broadcasters to reduce the communication needs.
- Establish a coordination board to deal with issues that develop by sharing data from disparate systems.
- Continue research in partnership with potential government users to ensure that future products meet their needs.
- Develop estimates of data archiving needs.
- Investigate potential classification issues.

Potential Experts

Coast Guard, Department of Defense Counter Narco Terrorism Project Development Office, Department of Homeland Security, instrument developers.

Data Management

Data from all SCM systems are similar as are the requirements for installing and maintaining the instruments. Hence, this SCM system network represents one component of IOOS in which centralized coordination and training will be beneficial. Once in place, data-sharing protocols and trained technicians created by the long-range backbone network will greatly reduce the marginal costs associated with adding additional, higher-resolution HF radar systems in specific regions.

Cost Considerations

Network cost estimates, including ranges, are provided in Table 1. The largest uncertainties are related to the total number of sites to be established and the operating costs associated with the most remote locations. Note that these funds would provide processed and quality-controlled radial currents from each site posted to a central processing site; standard, real-time vector current products would also be available. Site-specific and research-related products would incur additional costs. For purposes of this discussion, the term "site" refers to a single HF radar installation and the term "node" is used to designate the collection of sites operated by a group. The term central hub (CH) refers to a central office designed to retrieve data from each site, via the local SCM node, and produce common, user-defined products.

Table 1. Cost estimates for a nation-wide SCM network based on long-range HF radar units.

Initial Set-up			
Hardware Costs/Site	Installation Costs/Site*	Number of Sites**	**Total Costs**
$110,000 to $150,000	$40,000 to $70,000	100 to 200	**$15M to $44M**
Annual Operating Costs			
Node/CH Salaries***	Node/CH Maintenance	Node/CH Costs	**Total Costs**
$220,000 to $300,000	$30,000	$250,000 to 330,000	**$5.3M to $13.5M**

*Includes personnel time required scouting and preparing field locations.

**Depends on the density in Hawaii, Alaska and the territories, and on the desired redundancy nationwide.

***Based on 5 sites/node requiring 2 technicians/node; A single CH is budgeted at costs similar to a single node.

Recommended Next Steps

The SCMI Steering Committee is committed to continuing to define and improve the recommendations for a national backbone surface current mapping system. A timeline for these activities is presented in Figure 2. Immediate next steps include:

- Promoting additional programs to integrate surface current maps with user products and data-assimilating numerical models.
- Developing more-specific recommendations for pilot projects and phased implementation.

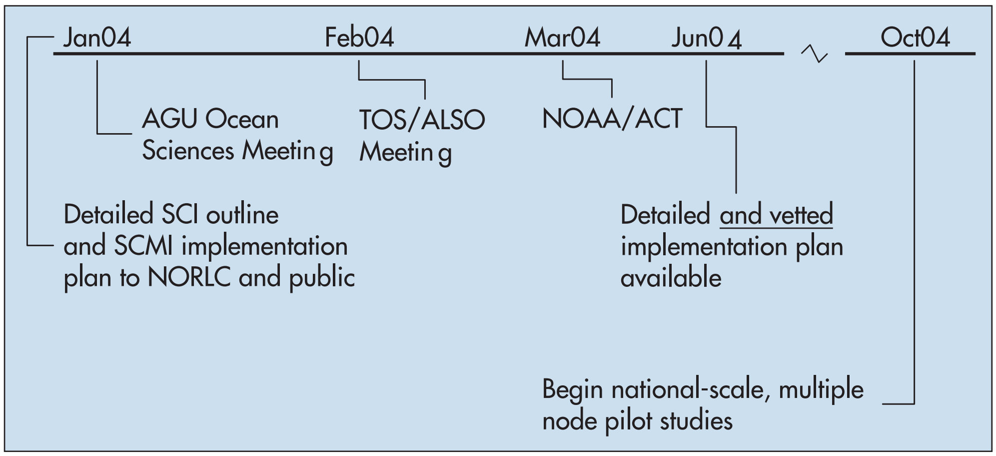


Figure 2. Schedule of SCMI activities in 2004.

SCMI Needs from National-Level Agency Planning Bodies

As mentioned above, the SCMI will benefit from centralized planning and execution. HF radar system installation, in particular, will benefit if the following agency actions are promoted by each of the IOOS organizing bodies:

- Provide high-level support for frequency allocation and siting issues.
- Assist in developing the governance model (Figure 3).
- Fund targeted research studies to improve all aspects of model data assimilation.
  - > This would bring together a team of HF users and modelers to publish what is known and outline future challenges.
- Fund SCM pilot or pre-operational projects. These projects should be considered as precursor to pre-operational and operational systems.
  - > Begin a large-scale pilot study immediately, given the large number of research efforts already underway using HF radar units.
    - A pilot study, in this context, is one that covers

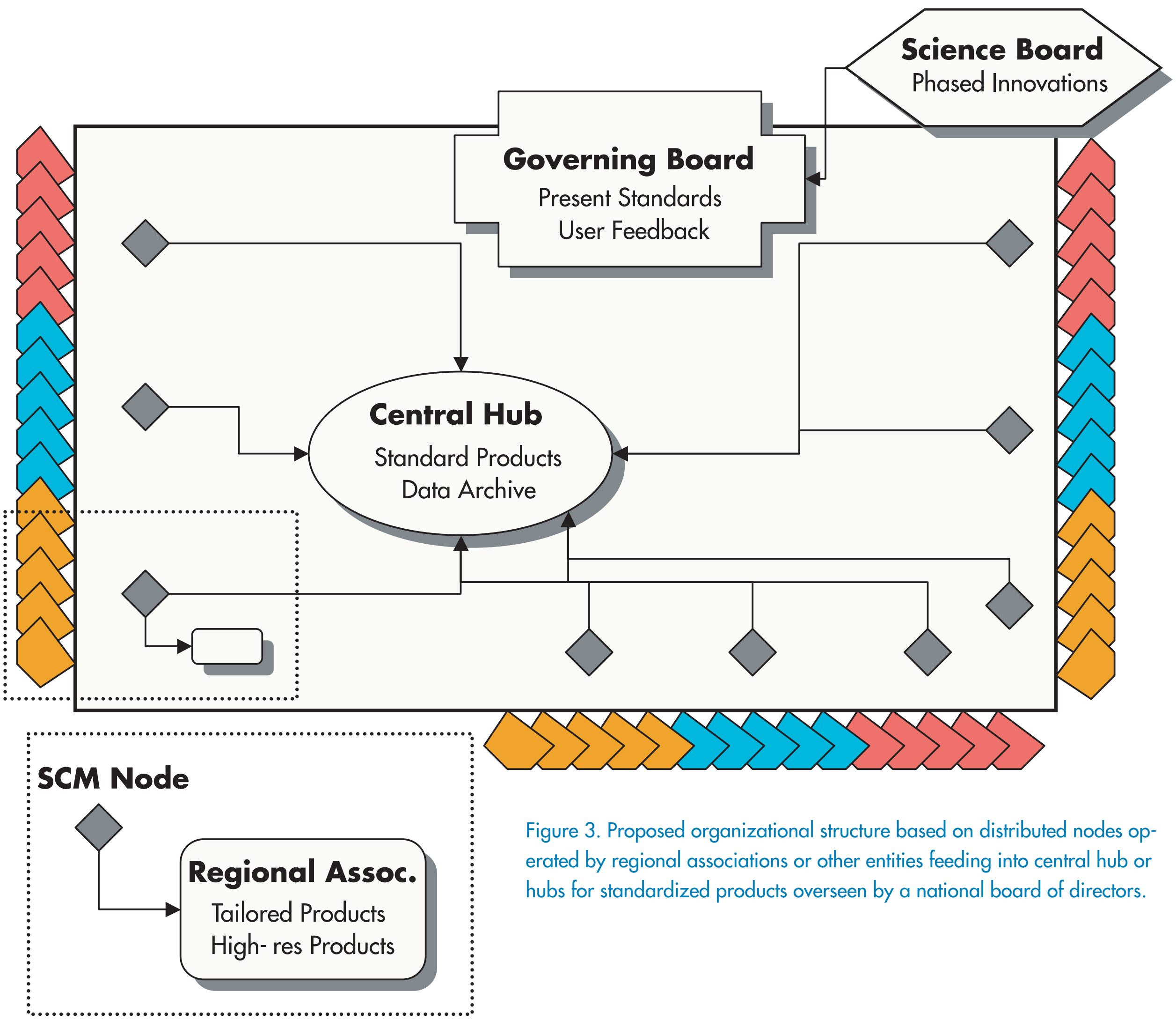


Figure 3. Proposed organizational structure based on distributed nodes operated by regional associations or other entities feeding into central hub or hubs for standardized products overseen by a national board of directors.

a significant fraction of the proposed national implementation plan. Significant financial investment is needed to include several "nodes" to demonstrate the challenges of data exchange and reliability.

- A pilot study using multiple nodes should also include a central hub to coordinate data flow and provide a single-point user interface.
- A pilot study would likely be based in regions with large numbers of existing HF radar installations; operators would have to agree to the data sharing and exchange (and reliability) specifications of the national system in exchange for operations funding.
- Later SCM system implementations would take place with new hardware probably owned by NOAA (or another agency) and contracted out to node operators around the country. This will "return" the existing systems back to the pilot study operators for other uses or for resolution enhancements.

References

Ocean.US, 2002, *Building Consensus: Toward an Integrated and Sustained Ocean Observing System (IOOS)*. Ocean.US, Arlington, VA 175 pp.

Appendix I

Examples of Existing Surface Current Mapping Capabilities

The following pages include a number of example results from installations of SCM systems around the country. They span the range of mapping scales from the highest resolution, lowest range implementations to the lower resolution, long range systems most closely aligned with the proposed framework for a national backbone SCM network.

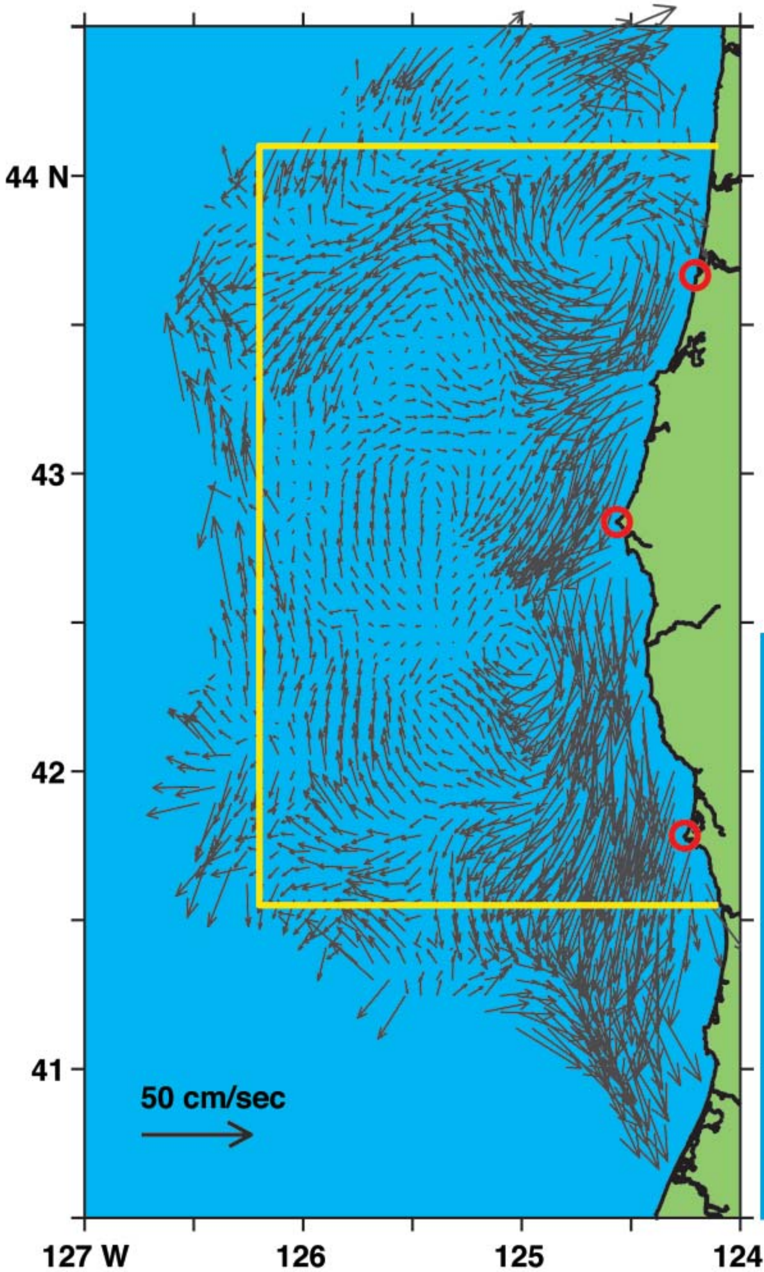
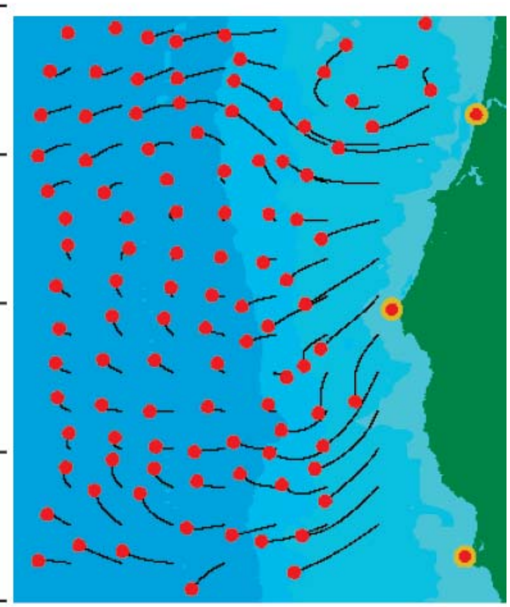


Figure 1. Low-pass-filtered surface currents offshore Oregon and northern California on 14 January 2002 showing alongshore flow interrupted by several mesoscale eddy features (left) and week-long particle trajectories ending on the same date computed from the surface current data illustrating the dominance of offshore transport during the period (right; *courtesy of Bruce Lipphardt*).



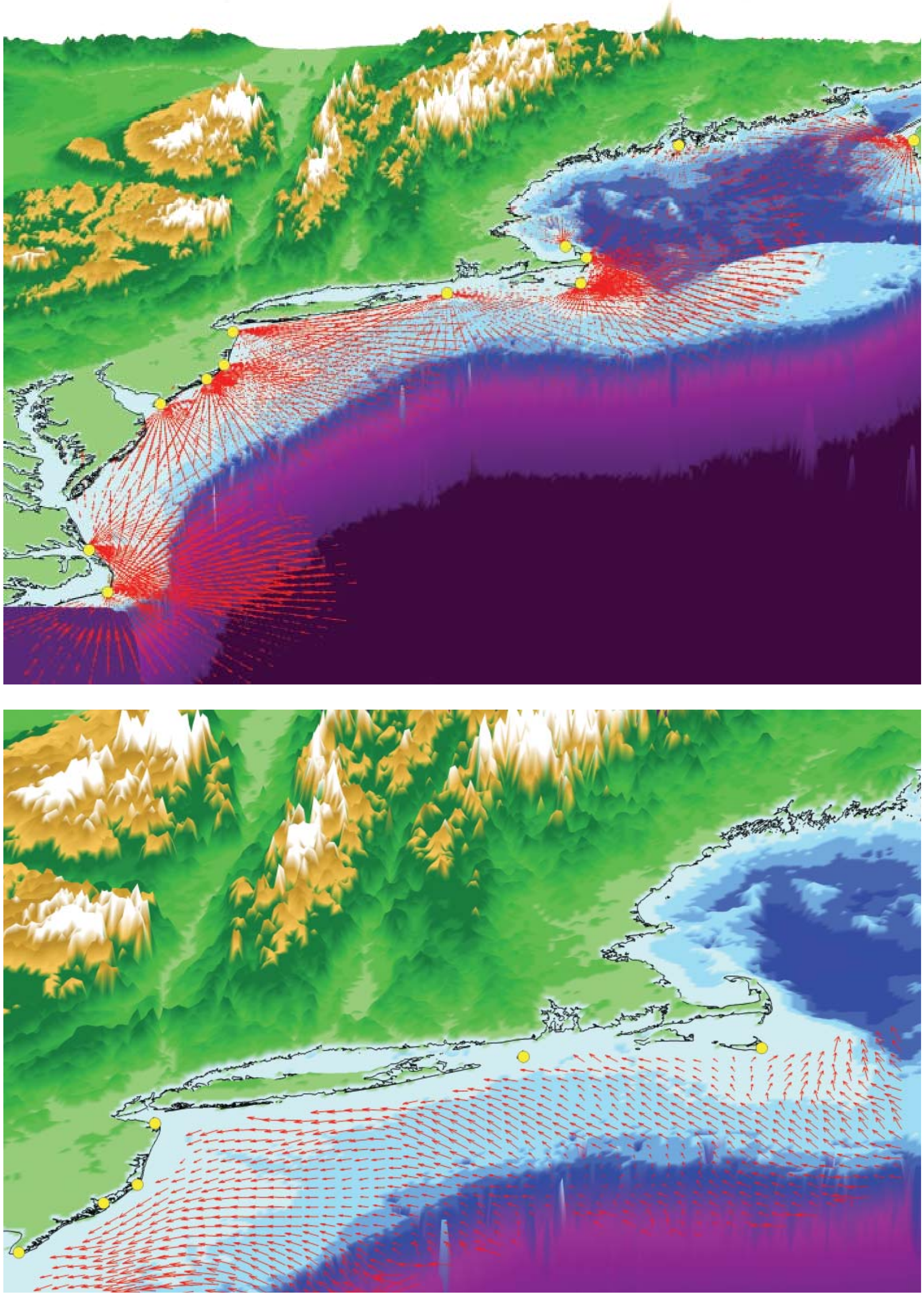


Figure 2. (a) Radial vector coverage of surface current data from long range HF radar systems along the northeastern seaboard of the U.S. as of May 2004. These sites are operated and maintained by academic and government partners of the NorthEast Observing System (NEOS). (b) A sample surface current vector map calculated over a region of overlapping radial coverage during the passage of Hurricane Isabel, September 18, 2003. The data for these figures were provided by the various NEOS partners operating the remote sites, total vectors were calculated using Mike Cook's HF Radar Toolbox (Naval Postgraduate School), and the figures were created by Josh Kohut and Scott Glenn (Rutgers University).

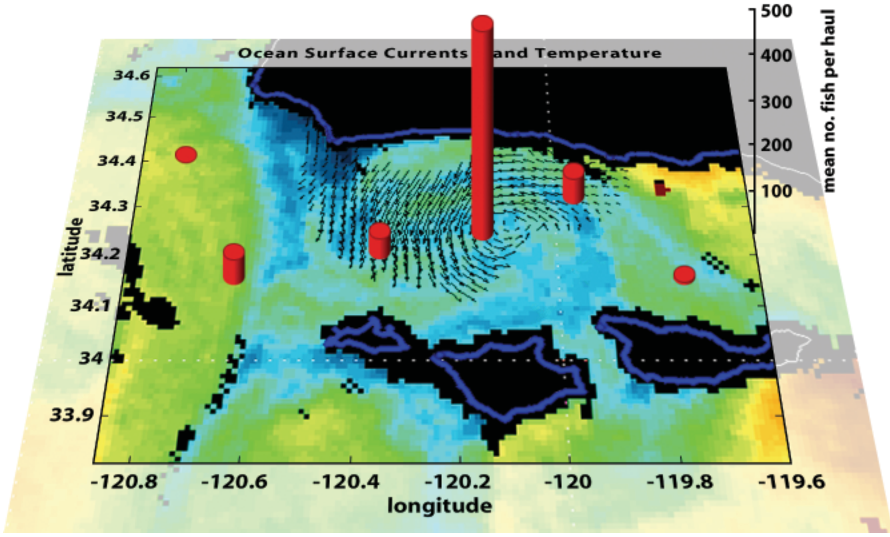


Figure 3. The distribution of pelagic juvenile rockfishes (*Sebastes jordani*) during 1-14 June 1998 in the Santa Barbara Channel (red columns) in relation to the surface flow pattern derived from high frequency radar. Surface current vectors (black arrows) show that a strong cyclonic flow was present and the highest abundances of rockfishes occurred near the center of rotation. Colors indicate satellite-derived sea surface temperature (red shades are warm and blue shades are cool); the maximum temperature temperature difference across the figure was about 5 °C. Circular bands in the temperature image are consistent with cyclonic rotation. The highest surface current speeds were about 0.3 m s^{-1} and the maximum relative vorticity was ~0.5 *f*, where *f* is the Coriolis parameter. The eddy-like circulation extended to at least 200 m based on hydrographic observations during fish sampling. Red columns and vertical axis show numbers of fish collected in net hauls at ~30 m depth. Columns are placed at representative sampling locations. Fish abundance was obtained from net tows (12 m x12 m net opening) with sample volumes of ~200,000 m^3. Sampling for juvenile fishes occurred over 2 weeks and levels of fish abundance in the eddy-like circulation exceeded levels outside by over an order of magnitude. Nishimoto and Washburn (2002) discuss these and related observations in more detail.

Nishimoto, M. M. and L. Washburn (2002) "Patterns of coastal eddy circulation and abundance of pelagic juvenile fish in the Santa Barbara Channel, California, USA", *Marine Ecological Progress Series*, 241, 183-199.

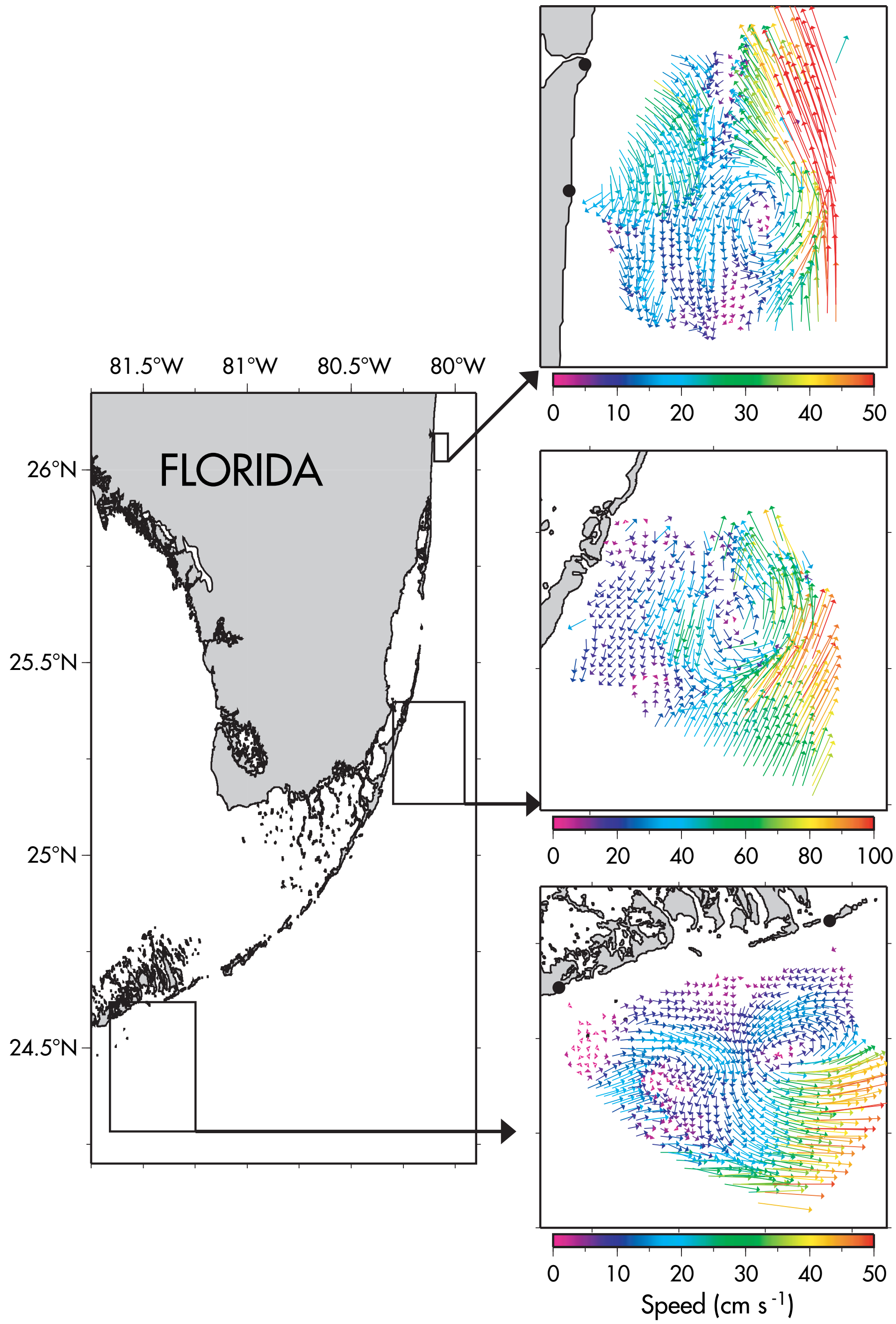


Figure 4. Observed surface currents using the VHF mode of the OSCR radar system from July 1999 (top panel; Shay et al., 2000), and the HF mode of OSCR for Key Largo in Feb 1998 (middle panel; Haus et al., 2001), and Bahia Honda Key in May 1994 (bottom panel; Shay et al. 1998) with the appropriate color bars depicting current speed.

Haus, B. K., J. D. Wang, J. Rivera, J. Martinez-Pedraja, and N. Smith, 2000: Remote radar measurement of shelf currents off Key Largo, Florida, USA. Esturine, Coastal and Shelf Sci., 51, 553-569.

Shay, L. K., T. N. Lee, E. J. Williams, H. C. Graber, and C. G. H. Rooth, 1998: Effects of low frequency current variability on submesoscale near-inertial vortices, 103, 18,691-18,714.

Shay, L. K., T. M. Cook, B. K. Haus, J. Martinez, H. Peters, A. J. Mariano, P. E. An, S. Smith, A. Soloviev, R. Weisberg, and M. Luther, 2000: VHF radar detects oceanic submesoscale vortex along the Florida Coast, EOS, 81, 209,213.

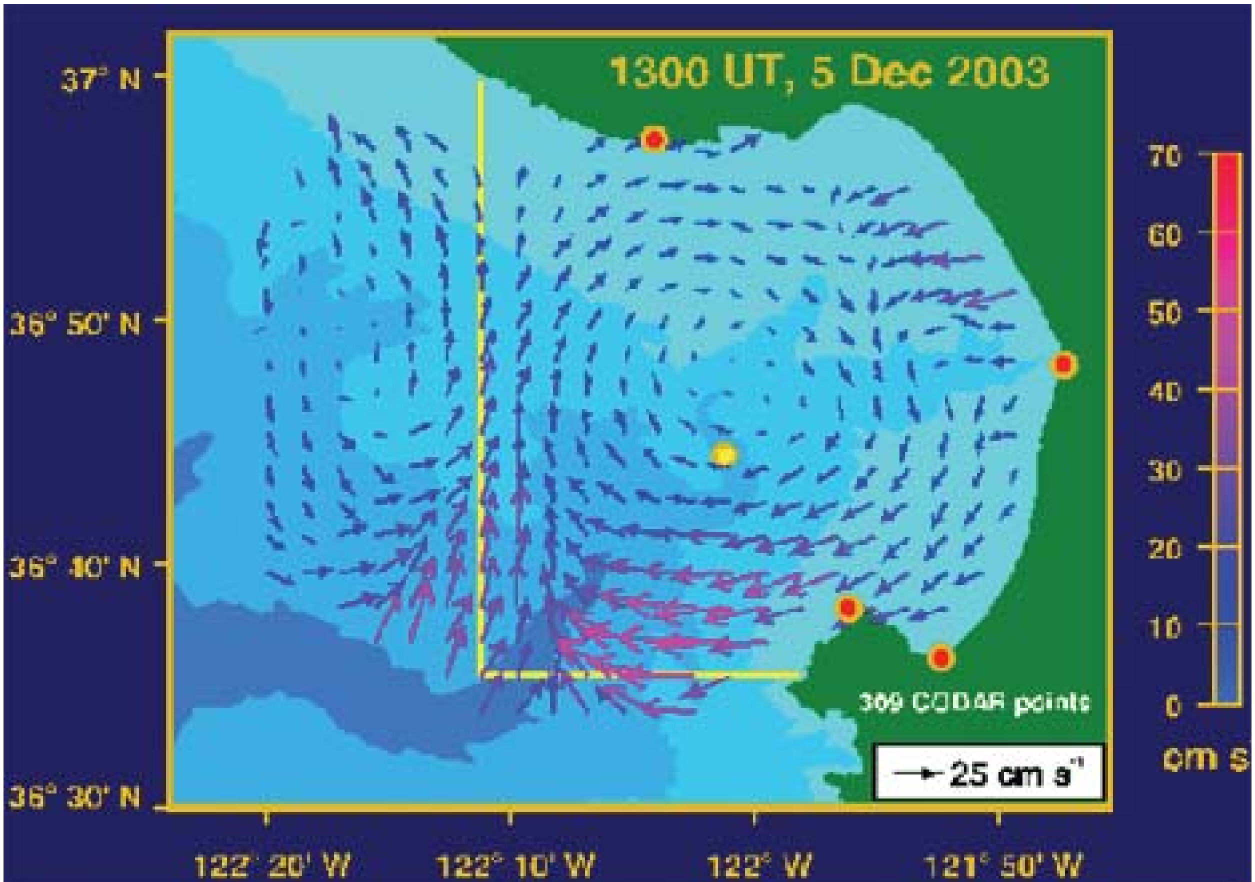
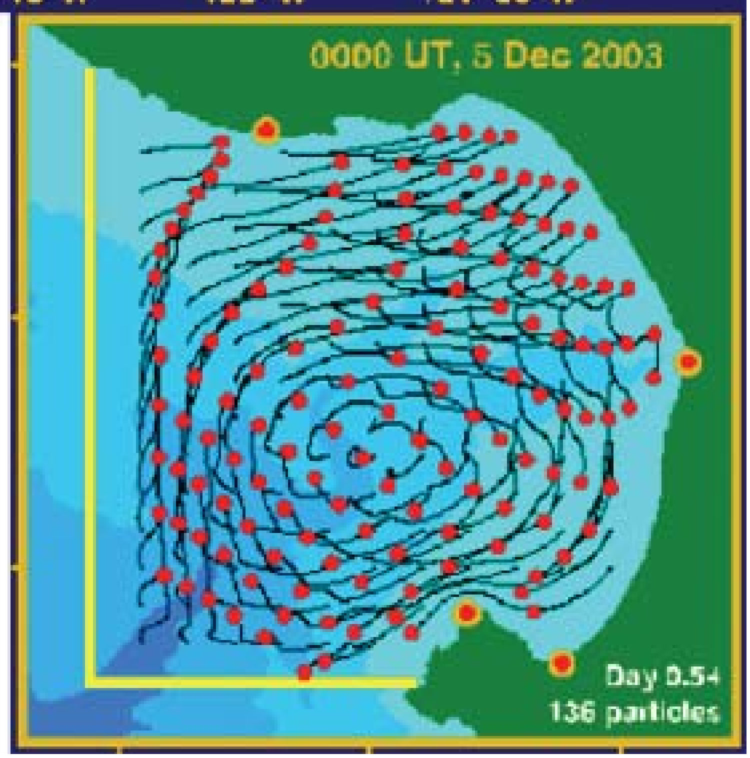
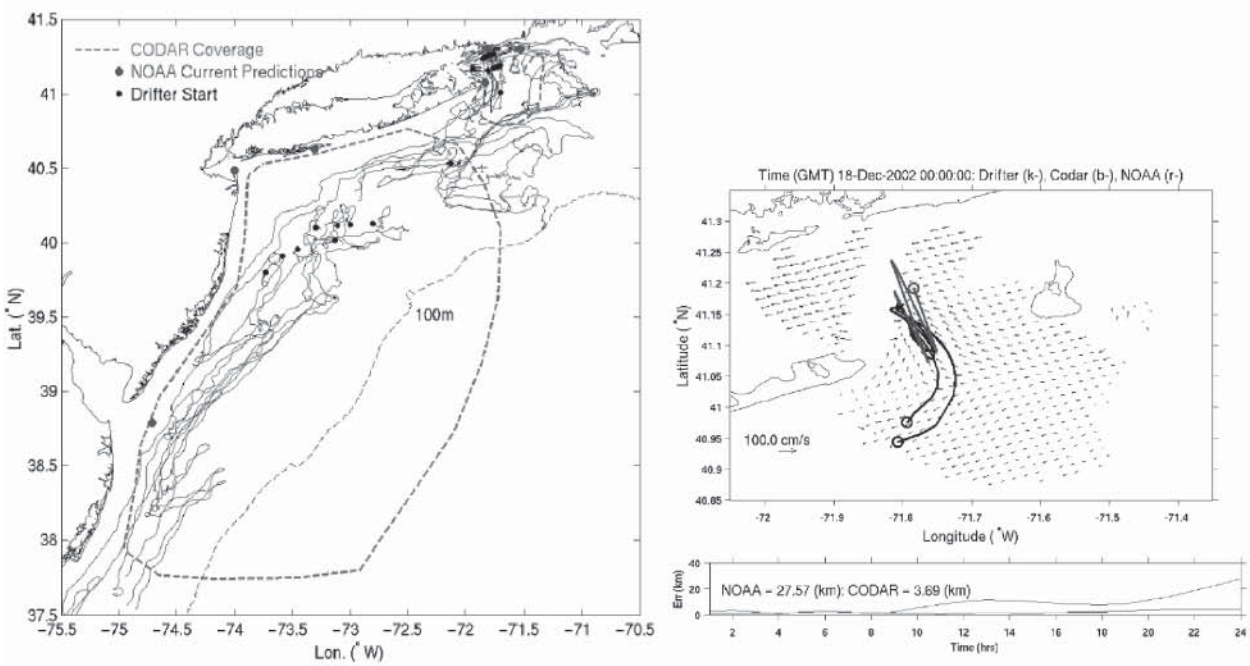


Figure 5. Sample surface current map for Monterey Bay, California (above) based on data from a 4-site, CODAR-type HF radar network (red symbols). Data from these systems are processed in real time, including a normal mode analysis mapping of the raw data within a smaller mapping domain (yellow box) that makes it possible to produce continuously updated surface particle trajectories (right). Real time products and more information can be found on the web site: http://newark.cms.udel.edu/~brucel/realtimemaps/





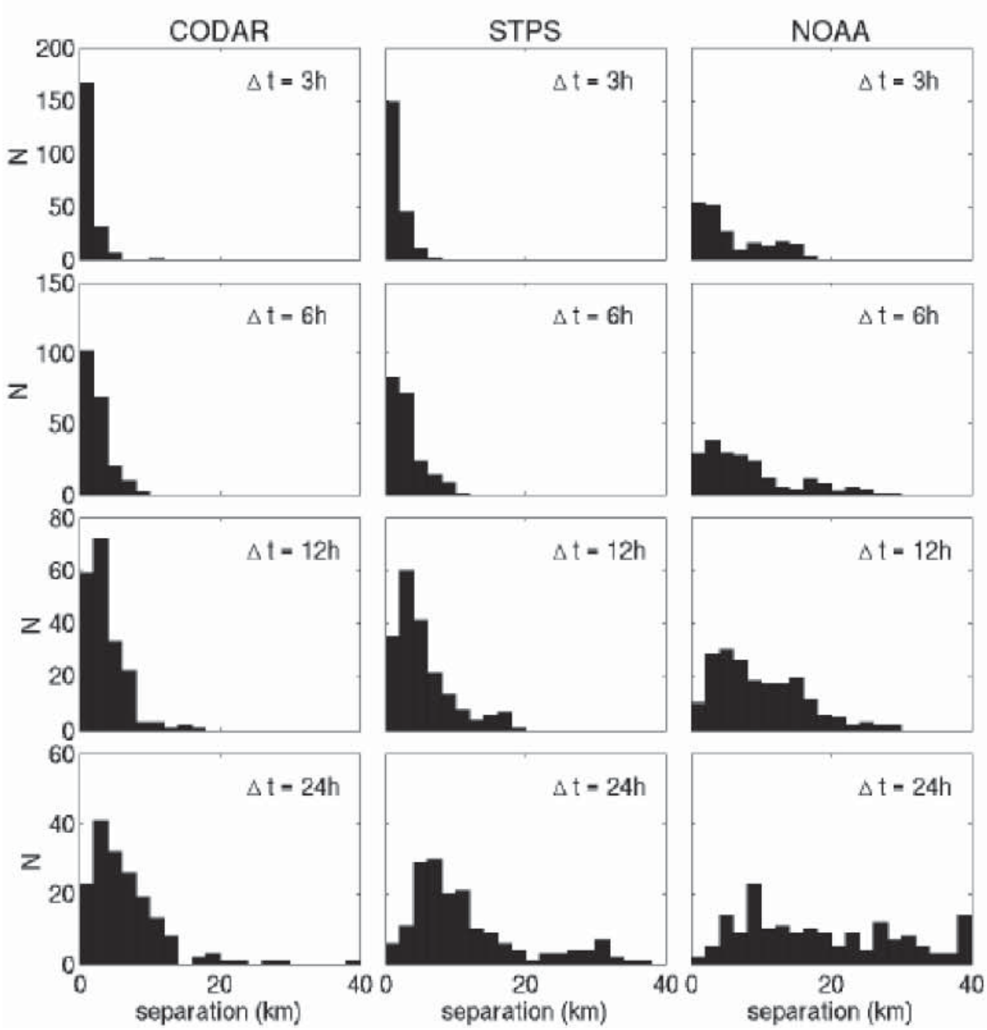


Figure 6. Trajectories of surface drifters deployed in Block Island Sound and offshore Long Island to be compared with synthetic particle trajectories computed from HF radar-derived surface current maps (upper left) and sample synthetic trajectories in Block Island Sound together with a single surface current map from the HF radar (CODAR) network (upper right). Histograms of the separation distance between actual drifters and synthetic drifters as a function of time (right) for the HF radar derived velocities (CODAR), for the HF radar plus model velocity forecasts (STPS) and from the standard prediction model (NOAA).

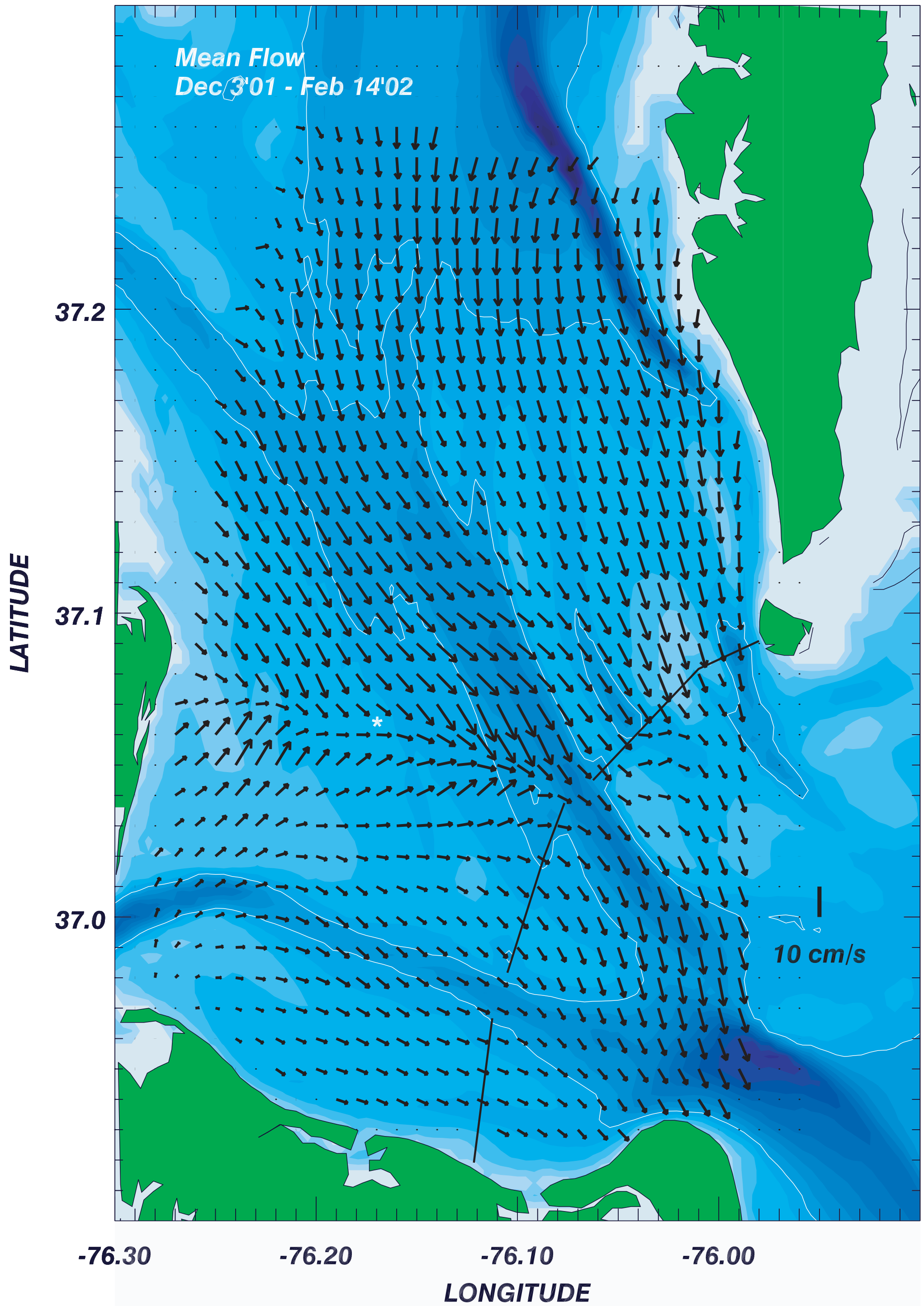


Figure 7. Mean surface currents over a three-month period in the lower Chesapeake Bay from CODAR (HF radar) data collected by NOAA-NOS/CO-OPS 2002-2003 and analyzed by Dr. Arnoldo Valle-Levinson at ODU/CCPO. Data were also analyzed for tidal components and compared to tidal currents observed at several Acoustic Doppler Current Profiler (ADCP) stations. See: http://www.ccpo.odu.edu/~arnoldo/ftp/LOWERBAY/CODAR/report.pdf. Figure courtesy of Arnoldo Valle Levinson, Old Dominion University with support from NOAA/NOS/CO-OPS.

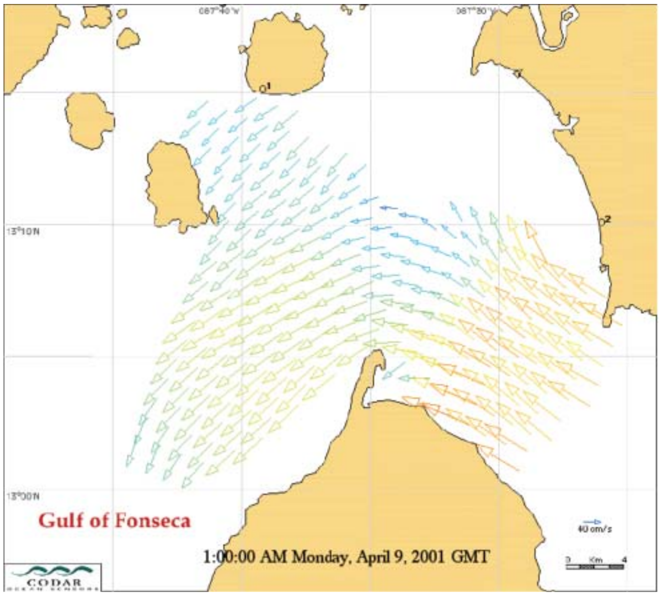


Figure 8. Surface currents in the Gulf of Fonseca, Honduras from a two-site CODAR/SeaSonde HF radar network deployed by CODAR Ocean Sensors, Ltd. under contract to NOAA-NOS/CO-OPS. The effort was in response to Hurricane Mitch and was designed to provide surface current information on the dispersion of runoff pollutants to the shrimp farming industry and others. This challenging remote site required the use of small generators and 24/7 security, but resulted in a high quality data set over a one-month period. Figure courtesy of CODAR Ocean Systems (under contract to NOAA/NOS/CO-OPS).

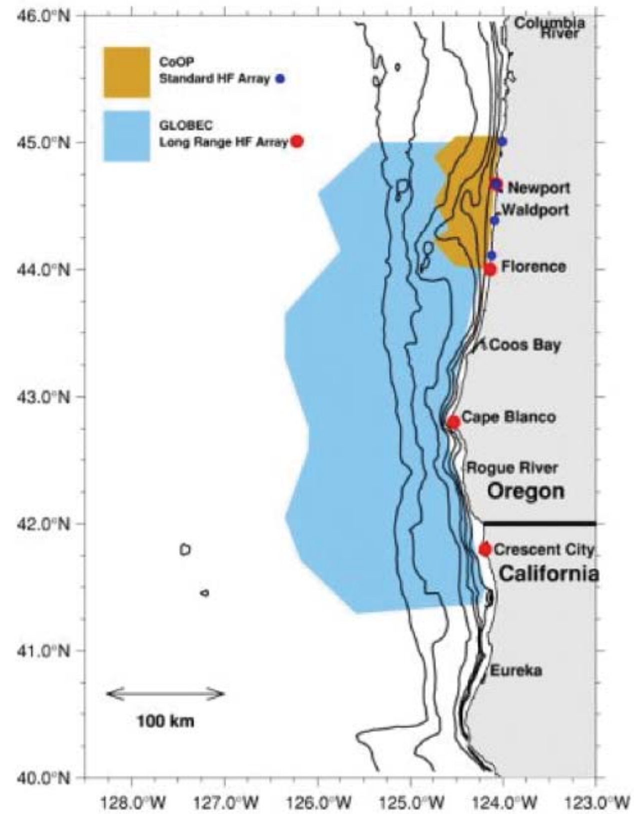
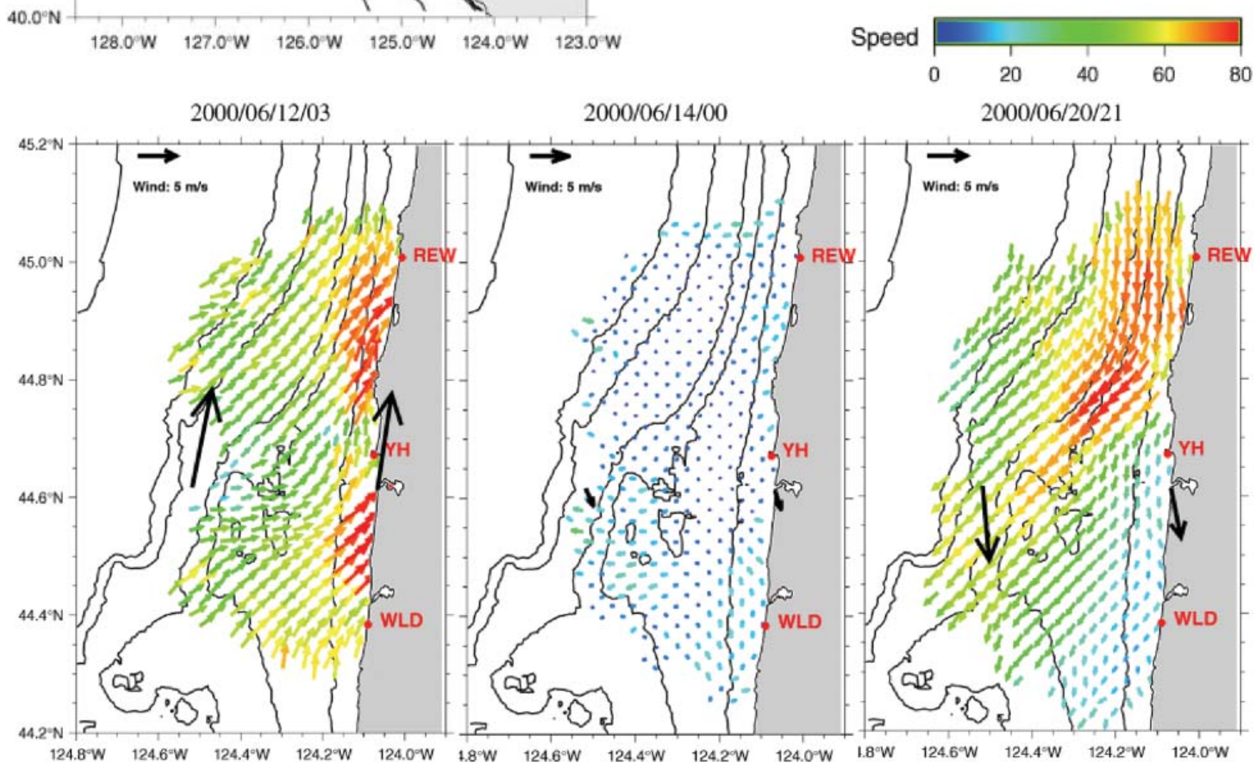


Figure 9. Schematic diagram of the surface current coverage areas for the standard and long range HF radar systems along the southern Oregon and northern California coasts (left). A sequence of surface current maps from the standard range network shows the reversal of currents in response to a reversal in the wind forcing (below). Note the velocity jet that was created during the upwelling-favorable (southward) wind conditions and how it flows offshore following the bathymetric contours of Heceta Bank unlike the nearshore velocity maximum during the northward wind event.



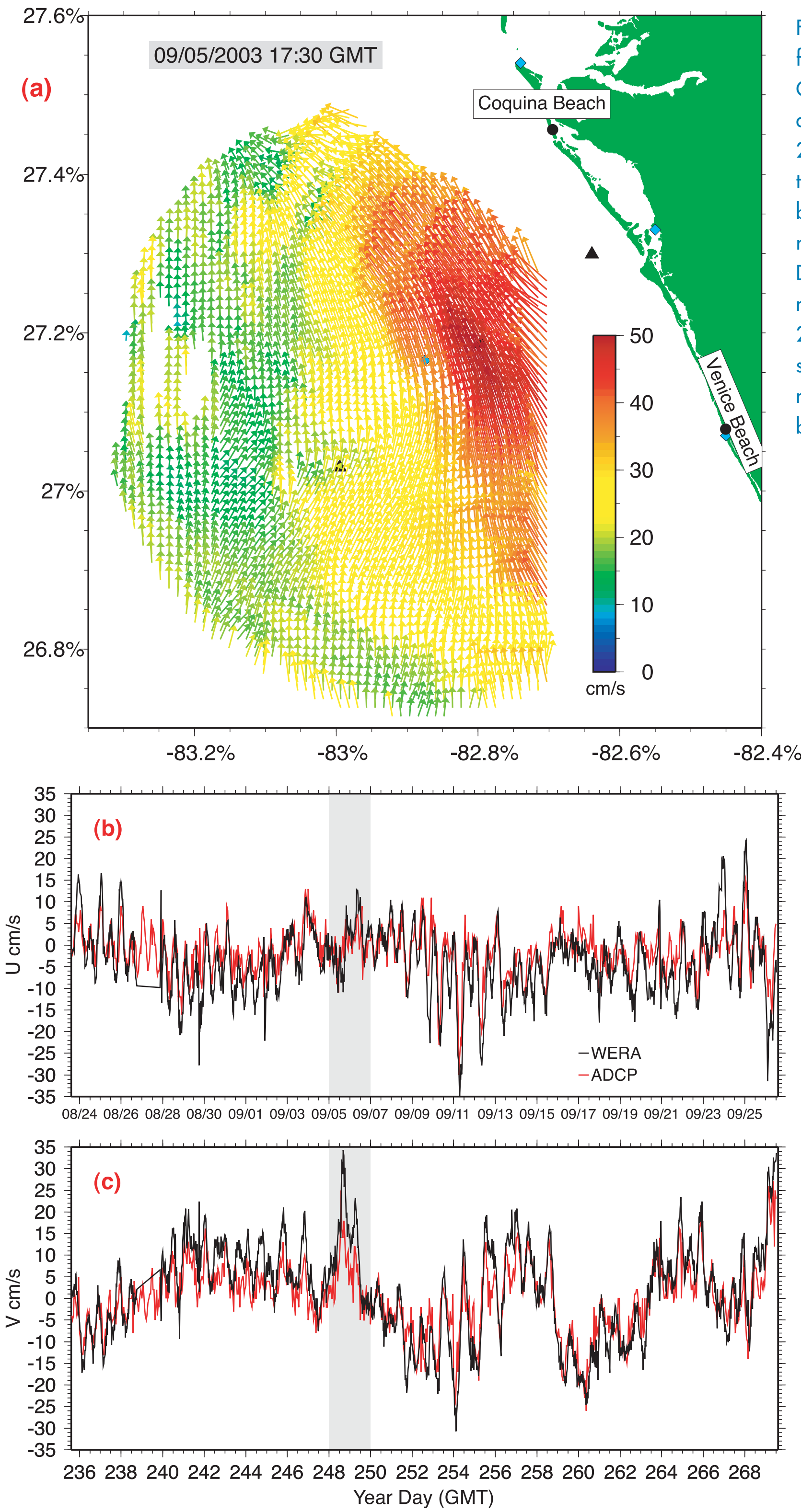


Figure 10. a) Example surface current image from the deployment of the SouthEast Atlantic Coastal Ocean Observing System Wellen Radar (WERA) on the West Florida Shelf in Sept 2002 during Tropical Storm Henri. The location of the moorings are indicated by triangles. b) and c) Comparison of WERA surface current measurements (black) and 3-m Acoustic Doppler Current Profiler currents (red). The mooring location is along the 25-m isobath at 27.16°N and 82.95°W indicated in a). Gray shading represents period of TS Henri. The mooring data are courtesy of Dr. Robert Weisberg at University of South Florida.