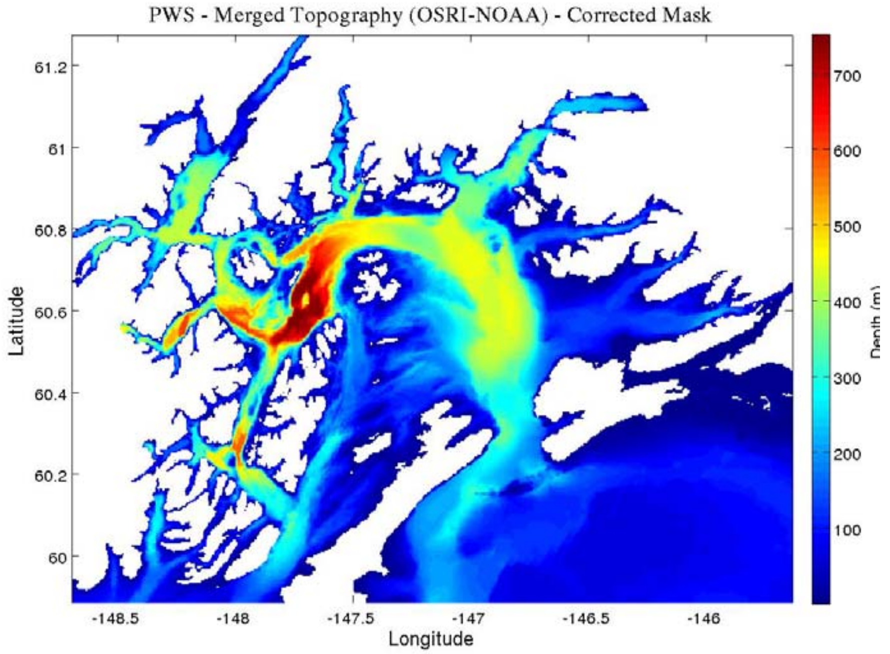
A Demonstration of the Alaska Ocean Observing System in Prince William Sound



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AOOS
Alaska Ocean Observing System

PRINCE WILLIAM SOUND
SCIENCE CENTER
CORDOVA, ALASKA

PRINCE WILLIAM SOUND
OIL SPILL RECOVERY INSTITUTE

NASA

Contributing Organizations

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3. University of Alaska Anchorage Alaska Experimental Forecast Facility
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Abstract

The Alaska Ocean Observing System (AOOS) and the Oil Spill Recovery Institute (OSRI) have over a period of five years developed an ocean observing system in Prince William Sound (PWS). This observing system now consists of a dense spatial array of atmospheric and oceanic sensors providing real time data directly to the public and to a new generation of weather, ocean circulation, wave forecast, and ecosystem models. A state of the art data management system at the University of Alaska Fairbanks provides access to these data and model forecasts from one data portal at www.aoos.org. In 2009 AOOS, OSRI, and NASA sponsored a field experiment in Prince William Sound to evaluate the utility of the sensor arrays and the accuracy of model forecasts. The objective of the experiment was to quantitatively evaluate the performance of forecast models including the PWS-WRF atmospheric and ROMS ocean circulation models, the SWAN wave model, the CoSiNE ecosystem model, and the SAROPS search and rescue trajectory model. The overarching questions are 1) How well are the models able to predict the weather, wave conditions, and circulation patterns in different areas of PWS?; 2) Has the accuracy or skill of modeled circulation forecasts for the central basin improved from those made during the 2004 field experiment?; and 3) What is the cost/benefit of the observing system for weather and ocean forecasting? The field experiment was preceded in the summer of 2008 by a table-top exercise to re-run historical observational data from 2004 through the new generation of data assimilation models. In the spring of 2009 there was an experimental model run utilizing real-time data streams from operational PWS observational platforms. During the July-August field experiment, drifting buoys were repeatedly deployed, retrieved, and redeployed during a three week period. CTD casts and AUV and glider transects were made to collect water column profiles. An HF radar array was deployed to map surface currents in the central basin. There was an emphasis on model validation of surface and deeper currents in the central basin but additional drifter deployments and observations occurred around the perimeter of the Sound. Five different Lagrangian drifter designs were used to simulate ocean currents, Coast Guard Search and Rescue targets, and oil spill trajectories. This report describes the history and evolution of the observing system in PWS, the field

experiments used to evaluate the performance of observing system components, as well as lessons learned and recommendations for future investments.

Executive Summary

To demonstrate the utility of an ocean observing and forecasting system with diverse practical applications—such as search and rescue, oil spill response, fisheries, and risk management— a unique field experiment was conducted in Prince William Sound, Alaska in July and August, 2009. The objective was to quantitatively evaluate the performance of numerical models developed for the sound with an array of fixed and mobile observation platforms.

Prince William Sound was chosen for the demonstration because of historical efforts to monitor ocean circulation following the 1989 oil spill from the *Exxon Valdez* tanker. The sound, a highly crenulated embayment of about 100 x 100 kilometers at approximately 60° N latitude along the northern coast of the Gulf of Alaska, includes about 6900 kilometers of shoreline, numerous islands and fjords, and an extensive system of tidewater glaciers descending from one of the highest coastal mountain range in North America. Hinchinbrook Entrance and Montague Strait are the two main deep water connections with the Gulf of Alaska. The economic base of communities in the sound is almost entirely resource dependent. For example, Cordova's economy is based on commercial fishing and Valdez's economy is supported primarily by the Trans Alaska oil pipeline terminal.

When the *Exxon Valdez* grounded on Bligh Reef in the northeast corner of the sound, the resulting oil spill followed a southwesterly trajectory with much of the oil stranding on island beaches before exiting the sound through Montague Strait. Since the incident, numerous studies conducted on oil spill-related impacts and ecological recovery have led to the development of a prototype ocean observing and forecasting system focusing on oil spill trajectories.

In 2003, the observing system included periodic hydrographic surveys, coastal weather stations, a high frequency (HF) radar array to quantify currents in the central basin, a 4 kilometer grid regional atmospheric model, and a Princeton Ocean Model (POM). A 2004 field experiment sponsored by the Oil Spill Recovery Institute (OSRI; http://www.pws-osri.org) evaluated the POM performance by comparing model nowcasts with surface circulation patterns measured by the HF radars and with the trajectory of 10 meter drogue and surface drifter buoys. Since 2005, the system has rapidly evolved to

integrate with the Alaska Ocean Observing System (AOOS; http://www.aoos.org) and to take better advantage of new technologies in real-time data telemetry and more sophisticated atmospheric and ocean circulation models. As a consequence, the sound now has one of the highest time-space densities of environmental observations and forecasts in North America.

The observing system provides real-time data directly to various user groups and helps with developing numerical models for forecasting weather, waves, and ocean conditions. These models include the Weather Research and Forecasting (WRF) model, Simulating Waves in the Nearshore (SWAN) model, and a Regional Ocean Modeling System (ROMS).

The July and August 2009 field experiment was designed to quantitatively evaluate how well the weather, wave, and ocean circulation models performed in predicting actual conditions. During the field experiment, the fixed array of observing system instruments was augmented by thermosalinograph surveys and additional vessel-based measurements of pressure (depth), conductivity (salinity), temperature, chlorophyll fluorescence, turbidity, and nutrients along latitudinal and longitudinal transects in the central basin. Also, nearly continuous measurements of temperature and salinity were collected using a Slocum glider and a REMUS-100 autonomous underwater vehicle (AUV). The AUV-based sampling provided continuous spatial and temporal data needed for improving model performance. Four types of drifting buoys were used to observe ocean circulation: Argosphere drifters and U.S. Coast Guard Self Locating Data Marker Buoys (from Metocean Data Systems), and Surface Velocity Program drifters and Microstar drifters (from Pacific Gyre). A total of 44 drifters were repeatedly deployed, retrieved, and redeployed in the central basin during a 16 day period spanning spring and neap tides.

The WRF atmospheric circulation model is run twice daily for short-term ocean and wave forecasts that are more accurate than those provided earlier by regional atmospheric models. U.S. National Weather Service forecasts with 45-kilometer grid spacing are used to provide the lateral boundary for the 4-kilometer WRF forecasts. Weather observations to validate the WRF forecasts are provided by 12 land-based weather stations and 5 U.S. National Data Buoy Center (NDBC) buoy-mounted stations.

Surface waves constitute an extremely energetic component of the physical oceanography affecting coastal Alaska. From a practical standpoint, information about the wave conditions in the Alaskan coastal areas is needed to assess the fate of oil spills, related recovery efforts, and safe vessel operations. The grid-based SWAN was developed because buoy and satellite altimeter measurements of waves in coastal waters suffer from spatial and/or temporal sampling limitations. The wave model uses data collected from three NDBC buoys for ongoing validation in the sound, as well as the Cape Suckling and Cape Cleare buoys for validation of the Gulf of Alaska wave field.

Ocean circulation forecasts are based upon a nested series of three ROMS domains with grid sizes of 9, 3 and 1 kilometer encompassing the Gulf of Alaska, the south central coast of Alaska, and the sound, respectively. Historical studies identified regional and local winds, coastal fresh water discharge, and tides as the primary driving mechanisms of local coastal circulation. A digital elevation model that includes glaciers, snow storage, and melting processes is used to incorporate fresh water discharge. A 3-dimensional variational data assimilation (3DVAR) method was implemented so that near real-time *in situ* and remotely sensed data (from high-frequency radars and satellites) can be assimilated to provide operational nowcasts which serve as the initial conditions for 2-day forecasts. Satellite sea surface temperature (SST) data include Moderate Resolution Imaging Spectroradiometer (MODIS), Geostationary Environmental Satellites (GOES), and Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E). With satellite and real-time observational data being assimilated into ROMS, the forecast skill during the 2009 experiment showed a significant improvement when compared to the 2004 experiment. An experimental ecosystem modeling component is now being added to the ROMS forecasts.

The 2009 experiment was a qualitative success and the various research teams are now in the reanalysis phase to provide quality control of the observational data and further improve model forecast performance. The quantitative evaluation of the model forecast will be reported in a series of separate technical articles.

Table 1. Budget Summary (5 year totals)

Program	**Funding Summary**					
	Organization Totals					Component Total
Observing System	OSRI	PWSSC	RCAC*	AOOS	NASA	
Snotel	200	95		90		385
NDBC upgrades	0	128		0		128
Nearshore Moorings	0	0		103		103
HE & MS Moorings	600	600		165		1365
Stream guage	0	0		10		10
Thermosalinograph	0	0		10		10
Hydrographic surveys	160	0		0		160
HF radar	0	0		648		648
WRF	230	0		20		250
SWAN	0	100	15	20		135
ROMS	180	300		450		930
NPZ	0	0		240		240
Biological sampling	0	0		65		65
Vessel charter	0	0	20	172		192
Data analysis	0			179		179
Data management	100			**		100
Coordination	50	0		84		134
Field Experiment						0
FE Coordination					121	121
Drifters	43				43	86
REMUS AUV				40		40
Slocum glider				20		20
Biological sampling						50
Satellite Imagery					109	109
SAROPS					60	60
Totals	1363	1128	35	2226	333	5135

*Prince William Sound Regional Citizens' Advisory Council: some or all of this funding was prior to 2009

**AOOS funds for a data management program at UAF are not included here

Table of Contents

Table of Contents - continued

List of Tables

List of Figures

List of Figures - continued

List of Figures - continued

List of Figures - continued

Introduction

The most highly populated region in Alaska is along the northern Gulf of Alaska (GOA). The primary stakeholders for an ocean observing system here are commercial and recreational fishermen, oil and gas, and the shipping and tourism industries. Prince William Sound (PWS) is located in the northeast corner of the GOA at about 60° N and includes an intricate network of tidewater glaciers, rain forests, offshore islands, and ocean. PWS is surrounded by the Chugach Mountains that reach 4,300 m and contains the most extensive system of valley glaciers in North America. Most of the land area is in or adjacent to the Chugach National Forest. With a shoreline length of about 6900 km, and a tidal range exceeding 6 meters, PWS has an enormously varied shoreline habitat of seastacks, reefs, rocky headlands, mud flats, eelgrass beds, wetlands, kelp forests, and cobble beaches.

Economy

The Trans Alaska Pipeline carries oil south from the Arctic coast to the Port of Valdez in northeast PWS. The oil is then shipped to southern refineries on large tankers, making the environment of PWS highly vulnerable to oil spills. During the 2000 census, only 6,865 people lived in the five communities in PWS. The largest communities are Cordova (population 2,454) and Valdez (4,036). Chenega Bay (86) and Tatitlek (107) are Alaska Native villages, and Whittier (182) is mostly non-Native. Only Valdez and Whittier have highway access to the state's main road system. Whittier has Alaska Railroad passenger and freight service. Cordova, Valdez, Whittier, Tatitlek, and Chenega Bay are served by the Alaska Marine Highway System. The economic base of the PWS communities is almost entirely resource dependent. For example, the Cordova economy is based on commercial fishing, primarily for pink and red salmon, and Valdez is supported primarily by the oil pipeline terminal.

Climatology

Atmospheric conditions are primarily established by the interaction of storms associated with the Aleutian Low and with the coastal mountains surrounding the GOA (Wilson & Overland 1986, Royer 1998). As a consequence of this interaction, the prevailing winds are cyclonic leading to positive wind stress curl over the basin and downwelling-favorable wind stress over the shelf throughout most of the year. Upon encountering coastal mountains, moist storm air masses are elevated and adiabatically cooled. This leads to very high rates of coastal precipitation along the coast. Much of this precipitation is presumed to enter the ocean relatively rapidly because of the steep terrain, except for in the winter season, when it is stored in mountain snowpacks. Downwelling-favorable winds are weakest in summer, build rapidly through fall to a winter maximum and decrease through spring. In contrast, coastal fresh water discharge is a maximum in fall, minimal in winter (when precipitation is stored as snow), and increases gradually through spring and summer due to melting.

The mean wind stress curl associated with the Aleutian Low drives the counterclockwise flow of the Alaskan Gyre. Along the continental slopes, this flow includes the broad, relatively sluggish Alaska Current in the eastern and northern GOA and its transformation into the narrow, swift southwestward-flowing Alaskan Stream in the western GOA. This boundary current system represents the northward branch of the North Pacific Current after it bifurcates offshore of the British Columbian coast. The Alaska Current and Stream provide the oceanographic connection between the GOA shelf and the North Pacific. These currents are generally swiftest over the inner slope and separated from shelf waters by a shelfbreak front. Both the shelfbreak front and boundary currents regulate exchange between the shelf and slope.

Over the inner shelf, the alongshore winds and fresh water discharge generate the Alaska Coastal Current (ACC). The ACC originates on the British Columbian shelf, flows counterclockwise around the GOA, and then enters the Bering Sea through the Aleutian Islands (Royer 1998). Variability in the ACC arises due to the upstream (east of PWS) integral of the seasonally varying along-shelf winds and coastal runoff. Seasonal variations in wind and coastal buoyancy-forcing give rise to large changes in the strength and density structure of the ACC (Johnson et al. 1988, Weingartner 2005). The ACC is narrow (<10 km), swift (30 – 100 cm-s^{-1}), and deep (~150 m) in winter and broad (~40 km), relatively sluggish (10 cm-s^{-1}) and shallow (<50 m) in summer. October is a transition month, during which time the ACC evolves from its summer to its winter structure as winds intensify and runoff increases. Nevertheless, maximum near-surface currents are typically observed in late fall (Johnson et al. 1988, Stabeno et al. 1995) associated with the strong baroclinic nature of the current at this time.

PWS communicates with the shelf through Hinchinbrook Entrance in the east and through several passes in the west, with Montague Strait being the most prominent. Hinchinbrook Entrance connects the shelf with the Sound's central basin where depths exceed 350 m. Two bathymetric troughs extend north from the central basin. A 300 m deep trough extends to the northeast and terminates in Valdez Arm. A second trough curves to the northwest, where it broadens to form a ☆ smaller basin connecting the upper Sound to Knight Island Passage and the passes along the southwest portion of PWS. The Sound's maximum depths occur here; depths exceed 700 m in the northwest basin and range from 300 to 600 m in Knight Island Passage. By contrast, the shelf immediately south of PWS is shallower and bathymetrically simpler. Indeed, the shelf south of the entrance is relatively shallow (~120 m) and flat, with the exception of Hinchinbrook Canyon. This canyon, with depths exceeding 200 m, extends from the shelf break to Hinchinbrook Entrance and acts as a conduit by which continental slope waters can reach PWS (Figure 1).

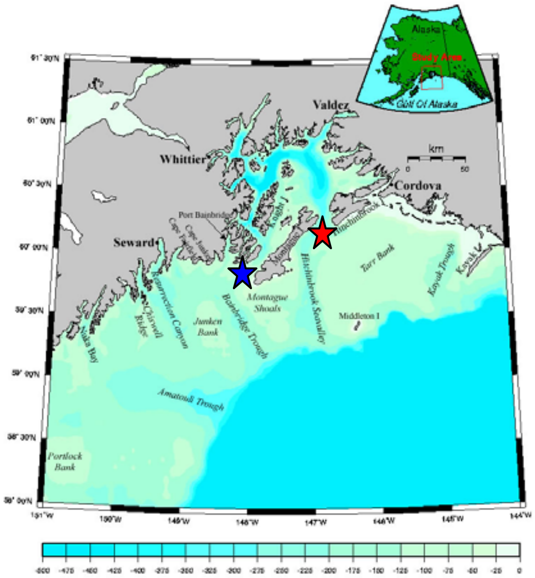


Fig. 1. Bathymetry of the continental shelf near and inside Prince William Sound. Hinchinbrook Entrance (red star) is located to the west of Hinchinbrook Island, and Montague Strait (blue star) is located to the southwest of Montague Island.

As the westward-flowing ACC encounters Hinchinbrook Entrance, a substantial fraction of it turns northward into PWS (Vaughn & Gay 2002). The remainder of this current continues across the mouth of Hinchinbrook Entrance, thence southwestward along Montague Island and westward again after rounding the southern tip of the island. Once in PWS, the flow often proceeds counterclockwise around the central basin, with some of the flow feeding the waters exiting through Montague Strait (and also perhaps along the western side of Hinchinbrook Entrance) and some of it continuing into the northern Sound (Schmidt 1977, Niebauer et al.1994, Gay & Vaughan 2001). Northern PWS waters flow southward through the Knight Island Passage and re-enter the shelf through southern Montague Strait and passes in the western Sound. This outflow and the branch of the ACC that has rounded the southern edge of Montague Island merge southwest of PWS and continue westward along the Kenai Peninsula.

There is also a significant exchange of deep (>150 m) waters between the shelf and PWS. This exchange occurs primarily through Hinchinbrook Entrance and also varies seasonally. Salty, nutrient-rich waters enter primarily in summer and fresher waters leave at depth in winter (Niebauer et al. 1994, Vaughan et al. 2001). The temperature and salinity properties of the deep summer inflow indicate that these waters derive from along the continental slope more than 100 km to the south of PWS. The deep inflow might also be an important conduit by which planktonic organisms and nutrients from offshore waters enter PWS. Hydrographic data collected as part of the GLOBEC program indicates that these waters flow northward across the shelf and into PWS primarily through Hinchinbrook Canyon as the adjacent shelf is relatively shallow. The deep water properties in winter are the result of vertical mixing between the dense summer inflow and the fresh surface waters of PWS that have cooled through fall and winter.

This circulation varies seasonally in accordance with the seasonal cycle of winds and runoff and appears to be strongest in late fall and winter and weakest in summer. Indeed, the counterclockwise circulation pattern might reverse occasionally, if not frequently during summer, with surface waters leaving through Hinchinbrook Entrance and entering through Montague Strait (Vaughan et al. 2001). As much as 40% of the volume of PWS above 100 m depth is exchanged in summer (May to September) and 200% is exchanged in winter (October through April) (Niebauer et al.1994). Although these estimates are uncertain, they nevertheless suggest that exchange between the shelf and PWS is substantial and efficient, and should therefore profoundly influence circulation and ecosystem processes in PWS. Studies of $^{13}C/^{12}C$ ratios in zooplankton confirm that a large percentage of carbon comes from sources outside PWS (Kline 1999). Moreover, it is conceivable that the timing, frequency, and magnitude of the exchange of water between PWS and the ACC is somewhat episodic and may vary considerably from year-to-year.

High latitude ecosystems such as PWS respond to a highly variable environment dominated by seasonal, annual, and decadal meteorological and oceanographic patterns. The hydrodynamic circulation is largely driven by meteorological, tidal, and fresh water buoyancy forces. But the exchange of water between PWS and the Gulf of Alaska is more complex and not fully understood. What was once thought to be a connected system with the Alaska Coastal Current flowing through PWS has been replaced by a new conceptual understanding supported by recent empirical studies and numerical models suggesting that the connection is episodic and seasonal (Figure 2).

Fig. 2. A conceptual diagram showing the exchange of water, nutrients, and carbon between the Gulf of Alaska and the coastal ecosystems (Source: EVOS/GEM Program document).

Biological Productivity

Phytoplankton biomass and production are strongly seasonal and highly variable. In general, massive spring phytoplankton blooms result from the availability of nutrients in the surface layer and the seasonal increase of daylight. High nutrient concentrations are observed in early spring over the entire GOA shelf due to winter entrainment and onshore Ekman flow of nutrient rich water from the central GOA basin. The spring bloom in the GOA persists until nutrient concentrations become limiting, and, thereafter, chlorophyll concentrations remain low. In PWS the spring bloom occurs as either a short, intense bloom when calm, warm weather results in strong stratification or a slower, prolonged bloom when cooler, stormier weather delays and weakens stratification (Eslinger et al. 2001). The spring bloom is initially dominated by diatoms, while later production is dominated by microflagellates (Horner et al. 1973, Alexander & Chapman 1980, Ward 1997). Studies associated with GLOBEC suggest that lower chlorophyll concentration in spring 1998 was associated with an intense warm ENSO phase. Enhanced stratification associated with El Nino reduces nutrient supply to the upper mixed layer and therefore biological production (Whitney & Welch 2002).

Zooplankton abundance is also strongly seasonal. Standing stock in PWS varies over 1.5 orders of magnitude seasonally (Cooney et al. 2001a), which is greater than oceanic and shelf populations in the northern and western GOA (Cooney 1987). The community of zooplankton in PWS is a mixture of coastal, middle, and outer-shelf species, probably because shelf and oceanic biomass is advected shoreward by wind and buoyancy-forced cross-shelf flow (Cooney 1986, Kline 1999, Cooney et al. 2001a). This spring seeding phenomenon results in an early spring zooplankton community with offshore affinities and a summer community of more neritic nature (Cooney et al. 2001a).

The dominant species of pelagic fish in the GOA in order of abundance are walleye pollock, pink salmon and Pacific herring. Average annual commercial harvest of walleye pollock is nearly 1.8 million kilograms. PWS is home to five fish hatcheries which release approximately 500,000 juvenile pink salmon annually. Growth rates of these fry may determine year-class survival (Parker 1968, Hart 1980, Bax 1983). A five-year ecosystem-wide investigation initiated in 1994, known as the Sound Ecosystem Assessment (SEA) study, addressed declining herring and pink salmon production in

PWS (Cooney et al. 2001b). The SEA study included bottom-up and top-down investigations of juvenile pink salmon and juvenile herring production and found that age 0 herring and juvenile pink salmon exploit very different portions of the annual production cycle but that both are dependent on ocean climate, production at lower levels, and to the abundances of specific predators (Cooney et al. 2001b). Large spawning concentrations of pollock and herring are found in PWS. Thousands of tons of Pacific herring spawn and are prey for many species of birds, mammals, and fish. The abundance of herring has drastically declined since the early 1990s, while pollock slowly increased during the same period.

The region is home to a rich and diverse marine ecosystem with large populations of birds, invertebrates, fish, and marine mammals. As part of the Pacific Flyway, PWS is a vital resting, feeding, breeding, and nesting area for more than 200 species of migrating birds that link PWS to regions as distant as Patagonia, the Gulf of California, and Hawaii. More than 100 bird species are year-round residents. Among these are over 6,000 bald eagles, a population larger than that found in the entire lower 48 states, as well as murres, puffins, and auklets. Black-legged kittiwakes build 16,000 nests annually (USFWS 2000), and PWS contains breeding sites for marbled murrelets and Kittlitz's murrelets, both of which are species in decline (Holleman 2003). Steller sea lions utilize the offshore rocks and reefs for haulouts, and 13,000 sea otters (USFWS 2003) forage in the kelp beds. A resident orca population of 360, and a smaller group of transient orcas roam the Sound.

Fisheries management in Alaska is often limited by the lack of information on how changing environmental conditions impact stock abundance. The dominant role of climate and ocean conditions in determining abundance for a wide variety of stocks and species is becoming increasingly apparent. Environmental forcing is suspected in those cases where age-structured abundance data are not adequate to explain stock status. Such a situation is illustrated by Prince William Sound herring. Based on age-structured modeling of stock abundance, the large biomass of herring in Prince William Sound in 1989 was expected to produce high catches throughout the 1990's. Nonetheless, the stock plummeted to very low levels in 1993, only two commercial openings have occurred since then, and stock levels remain very low almost two decades after the crash.

A wide variety of individual mortality factors (disease, predation, Exxon Valdez oil spill) have been hypothesized by way of explanation. Unfortunately, even when measured, the effects of individual factors on population size may not be identified due to the confounding effects of unmeasured environmental factors. Environmental data and forecasts are absolutely essential to understanding the dynamics of this ecosystem and better management of stock abundances.

Historical Nowcast/Forecast Efforts

The OSRI and its partner organizations conduct research in Prince William Sound to enable detection and prediction of oil-spill related impacts and subsequent recovery. This mission led to the development of the Nowcast-Forecast modeling effort that consisted of an atmospheric circulation model coupled to an ocean circulation model. As part of this strategy OSRI also provided funding support for new infrastructure with the intent to pursue additional development through partnerships and competitive grants. Funding secured in 2004 by the PWSSC allowed for infrastructure expansion such as improving the consistency and data quality of the existing array of meteorological sensors, deploying solar radiation sensors and precipitation gauges in the surrounding watersheds, redeploying a stream discharge gauge on the Copper River, and developing a synoptic wave model to predict wave heights, nearshore currents, and wave-induced turbulence. Additional funding from NOAA was secured by the PWSSC in 2004 through the Exxon Valdez Oil Spill Trustee Council to begin understanding the mechanisms and exchange rates of waters between the Gulf of Alaska and the Sound using fixed moorings at Hinchinbrook Entrance and Montague Strait, and collaborating with the GLOBEC team to develop a data assimilation model for PWS. Understanding the circulation and the patterns of water exchange will provide a solid scientific foundation for improving not only forecasts of oil spill trajectories and search and rescue targets, but also fisheries and ecosystem management related to long term oceanic and climatic variability.

Oil Spills

In the event of an oil spill, the USCG is designated as the Federal On Scene Coordinator (FOSC). NOAA provides scientific staff to advise the USCG on expected spill trajectories based on modeled scenarios from the General NOAA Oil Modeling Environment (GNOME) using any available data on winds and currents. This information is used to manage the oil spill including the deployment of diversion booms to protect sensitive habitats, aerial bombardment to ignite the spill, or to application of chemical dispersants. The real time data streams and model outputs of the PWSOS are used to inform NOAA on prevailing and forecasted atmospheric and oceanic circulation so that more accurate trajectories can be predicted. This approach will improve the assessment of risks versus costs, a key element in identifying the best oil spill prevention and response technologies. Current approaches to this system of oil spill response involve one-off solutions to data acquisition and model integration. An improved approach will provide NOAA with an online data flow of model output and instrument measurements for specific locations as well as general regions.

Search and Rescue and National Security

Prince William Sound and the Port of Valdez are considered by the U.S. Coast Guard as high risks from a national security perspective. While the possibility of another accidental oil spill has been contemplated since the Exxon Valdez spill in 1989, only recently has the prospect of sabotage become significant. Accurate models of the oceanographic, atmospheric, and biological systems in Prince William Sound may be critical to security and to search and rescue operations, therefore, the USCG will benefit from access to real-time data streams from this project.

Industry

PWS is home to five salmon hatcheries that produce pink (*Oncorhynchus gorbuscha*), sockeye (*Oncorhynchus nerka*), and chum (*Oncorhynchus keta*) salmon fry. In 1999, over 50 million adult hatchery salmon were taken from PWS, the highest number on record. Environmental monitoring information are important to the salmon hatchery industry operating in PWS. These hatcheries typically release juvenile fry stage salmon in the spring following the onset of plankton blooms. Critical elements to the survival of salmon include the release of salmon fry coincident with the spring plankton blooms, and currents conducive to flushing the young salmon out to sea. Returning adults require currents strong enough to provide a signal to lead them back to the hatcheries or natal streams. The ocean observing system products most useful to these industries are daily values of SST, salinity, current velocities, and 2 day forecasts, preferably emailed directly to the hatchery managers. Synthesized products of value to these operations are comparisons of present values compared to historical years, i.e. in the case of the salmon hatcheries, managers need to compare present conditions to historical conditions that have known salmon returns. Salmon hatcheries are a multimillion dollar business, and most of the expense is in fish food. The longer the salmon fry are held in pens awaiting the optimal conditions for release, the more food they require. The accurate management of fry release may improve the survival of fry to the adult stage and also decrease the unpredictable variability of adult returns.

Ecosystem Management

The goal of the PWSOS is to combine hypothesis-driven long-term research with short-term process studies to understand mechanisms underlying long-term dynamics between the major coastal currents of the GOA, the coastal ocean, and the fauna and flora of PWS. Of particular interest are understanding predominant causes of ecological variability. The central overarching ecological hypothesis is that both the degree and source of connectivity of PWS to neighboring coastal marine systems combined with natural and anthropogenic disturbances drive variation in ecosystem processes, community structure, and population dynamics over space and time. Critical connections between PWS and other ecosystems are forged through variable water mass exchange with the GOA or from coastal fresh water runoff, implying dramatic differences in heat, salt, nutrient fluxes, stratification, planktonic propagules, and dissolved and suspended inorganic particles. This temporal and spatial variation in inputs interacts with various disturbances from ecological processes, e.g. predation, human activities, earthquakes, and has important direct and indirect impacts. An expansion of the Nowcast-Forecast modeling program has potential utility in fisheries oceanography and in gaining a better understanding of the PWS ecosystem.

Nowcast/Forecast Infrastructure Expansion

The evolution of the OSRI Nowcast/Forecast System into the PWSOS allowed better utilization of infrastructure contributed by a host of partner organizations including the Prince William Sound Regional Citizens' Advisory Council, the National Data Buoy Center, the Natural Resources Conservation Service, the University of Alaska at Fairbanks, Anchorage, and Juneau, the U.S. Forest Service, the U.S. Coast Guard, and the Exxon Valdez Oil Spill Trustee Council. The role of OSRI in the PWSOS is to maintain the core components (e.g. met stations, ecological observations, circulation models) and is planned to continue until other funding sources are found (e.g. IOOS) or until 2010 whichever comes first. AOOS adopted the PWS effort as a pilot project for the development of a coastal ocean observing system and data management model to serve the future Alaska nodes in Southeast Alaska, Lower Cook Inlet, the Bering Sea, and the Arctic Ocean.

In 2005 the PWSOS consisted of a broad spatial array of sensors, maintained by both government and private entities, providing meteorological, oceanographic, and tidal data in real time (Figure 1).

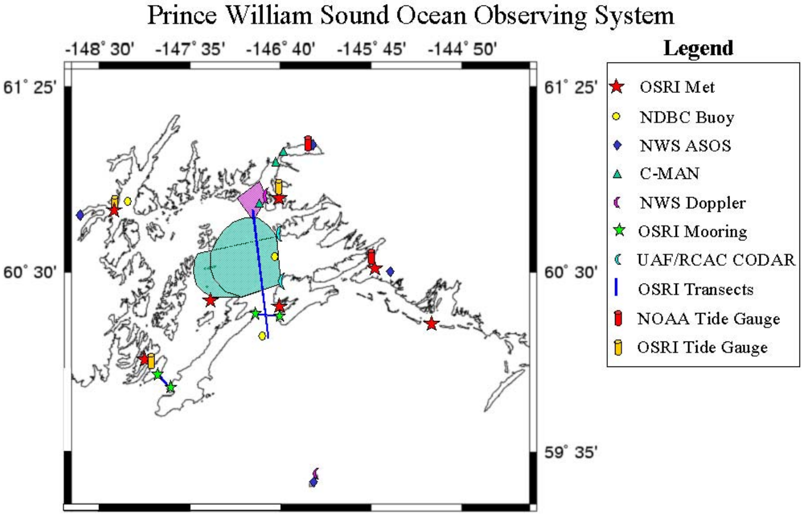


Fig. 3. The status of PWSOS in 2005.

The ocean circulation model operating from 2003 to 2007 for PWS was based on the Princeton Ocean Model (POM). The PWS-POM was forced by winds from the atmospheric circulation model. Tidal heights and currents were computed from tidal harmonics (amplitudes and phases) interpolated from a Northeast Pacific tide model. Wind stress was computed by the Regional Atmospheric Modeling System (RAMS), which is a mesoscale-resolving atmospheric model operated by the Alaska Experimental Forecast Facility (AEFF). Fresh water runoff was derived from a hydrological model (Wang et al 2001) and applied at the surface grid points next to the land. RAMS-driven forecasts were made out to 36 hrs. Heating and cooling were given by the climatological monthly heat flux from the Comprehensive Ocean and Atmospheric Data Set (COADS).

The limitations of the POM modeling effort were significant and included: 1) validations and verifications of the POM were limited to a single-point (i.e., no spatial variation) hourly observations of wind speed and direction at NDBC buoy 46060 (mid-Sound), 2) there were few observational data from Hinchinbrook or Montague Entrances for boundary conditions, 3) there were no nested larger scale domains to provide boundary conditions, 4) there were no real time measurements of precipitation or heat flux, 5) there were no real time measurements of tides, 6) and the POM was not able to assimilate the real-time data being collected by the PWSOS.

2004 Field Experiment Results Summary

A 2004 field experiment sponsored by the OSRI evaluated the POM performance by comparing model nowcast model results with surface circulation in the central basin measured by HF radars and with trackable surface and 10 meter drogued buoys. The field experiment results are described in detail by Cox (2005). The key findings were:

1. The surface and 10-m drogued drifters indicated a cyclonic gyre in the central basin.
2. Short strong wind events significantly influenced the trajectories of the surface drifters.
3. Relatively small differences in position at deployment sometimes led to different trajectories of surface drifters.
4. The speed of the 10-m drogued drifters was significantly lower than the speed of the surface drifters.
5. The 10-m drogued drifters stayed in the gyre area longer than the surface drifters (~286 hours vs ~40 hours).
6. The ocean circulation model “under-performed” and did not satisfactorily reproduce drifter trajectories.

AOOS Demonstration Project in PWS

The Nowcast/Forecast program evolved into the Prince William Sound Observing System in 2005 when the OSRI Board approved the funding for a 5 year effort to expand the program and partner with the regional Alaska Ocean Observing System (www.aoos.org) on a demonstration project in PWS. The AOOS partnership integrated the local effort into initiatives developing national and global ocean observing system (ioos.gov). The goals of the regional and national efforts include improving: 1) the safety and efficiency of marine operations; 2) predictions of climate change effects; 3) management of ecosystem, fisheries and water quality; 4) management of coastal hazards; and 5) coastal and marine spatial planning. While some government agencies already provide much of this information, the PWSOS can identify and work to fill observation and information gaps, and also supply tailored products to meet the needs of scientists, educators, industry, resource managers, search and rescue, and security agencies.

The PWS observing system now has a broader mission with two primary goals. The first goal is to understand mechanisms underlying the dynamics of the interactions between the major coastal currents and the production of flora and fauna of the Pacific Ocean, the Gulf of Alaska, and PWS. Of particular interest is the understanding of predominant mechanisms of ecological variability. Understanding the circulation and the patterns of water exchange will provide a solid scientific foundation for addressing fisheries management and ecosystem needs related to long term oceanic and climatic variability.

The second goal is to provide real time environmental information to the major user groups in PWS including the coastal communities, oil and gas transportation industry (tanker traffic and oil spill response), air taxis, commercial fishermen, recreational and commercial boaters, and Coast Guard search and rescue operations. Oil spill response and the search and rescue operations are highly reliant upon accurate and timely surface current information. The computer simulations under development by the Alaska Ocean Observing System (AOOS) will greatly improve the response time to marine accidents. For example, the high-resolution wind, wave and ocean current forecast products will provide improved weather forecasts to commercial and recreational vessel and aircraft operators, and it will enhance the safety of oil tanker traffic in PWS. The improved physical and ecological forecasting products will also enable resources managers (e.g., PWS hatchery and commercial fishing organizations) and government regulatory agencies to make better management decisions on food supply, predation, and human activities such as commercial and recreational fishing.

The key components of the ocean observing system in PWS include a relatively dense spatial array of automated weather stations, wave gauges, and ocean sensors including salinity and temperature recorders, current velocity profilers, as well as phytoplankton chlorophyll sensors. These are described in more detail below. In addition, a strategic data management program was designed so that AOOS is providing access to real-time weather and ocean observations as well as model generated forecasts for PWS from a single data portal (www.aoos.org).

The climate at high latitudes is a function of seasonal and interannual temperature variation that in turn drive regional and local winds, precipitation, and currents. Large tidal ranges that force currents and expose vast amounts of shoreline to the twice-daily ebb and flood also influence the northern Gulf of Alaska. This physical heterogeneity in time and space explains much of the biological variability observed in fisheries, birds, and mammal populations, as well as less charismatic benthic and pelagic invertebrate and plant communities. Therefore, an understanding of this physical variability is paramount to understanding the variability of the PWS ecosystem and was the initial focus, or bottom-up approach (i.e. physics first), of the observing system.

Observational Components

Meteorology: Weather stations at sea level

The PWSSC contracted the Natural Resources Conservation Service (NRCS), Micro-Specialties Inc, and the Alaska Meteorburst Communication System (AMBCS) to replace six meteorological stations in PWS in 2004 (Figure 2). The upgraded stations included the standard NRCS Snowpack Telemetry (SnoTel) meteorological sensors as well as precipitation and solar radiation sensors. As of the spring of 2010 all of these stations were functioning normally except for Nuchek which was not communicating data.

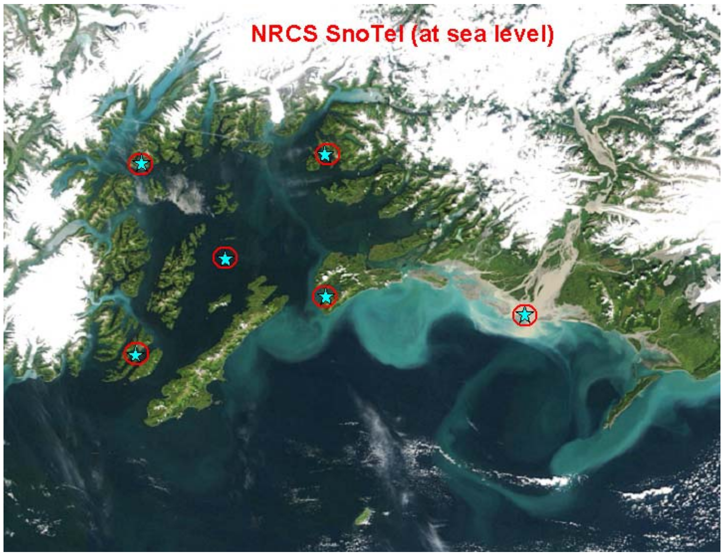


Fig. 4. Locations of 6 sea level SnoTel meteorological stations in PWS.

Meteorology: Weather stations at elevation

The PWSSC and AOOS partnered with the NRCS in 2005 to establish precipitation gauges at about 500 m elevation (~treeline) on Mt. Eyak, Naked Island, Mineral Creek near Valdez, and in College Fjord. Two automated weather stations were funded by a NOAA grant to the PWSSC, and three stations were funded by AOOS. The intent was to quantify the horizontal and vertical precipitation gradients in PWS (Figure 3). Only the two stations funded by the PWSSC were deployed. The three stations proposed for deployment in the western portion of the sound were delayed by permitting issues and then finally cancelled.

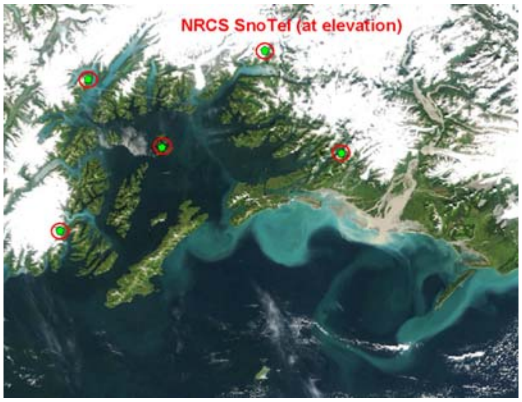


Fig. 5. Locations for proposed SNOTEL precipitation gauges at 500 m elevation.

Oceanography: National Data Buoy Center

The PWSSC partnered with the National Data Buoy Center (NDBC) to demonstrate the utility of weather buoys as platforms for in-water sensors. Through a grant from NOAA, the PWSSC purchased three RDI ADCP's and three Seabird Microcats for deployment on existing NDBC buoys. The original project was to instrument weather buoys in Hinchinbrook Entrance (HE) 46061, the Central Basin 46060, and deploy a new buoy in Montague Strait (MS). Instead a new weather buoy in College Fjord 46081 was instrumented and deployed (Figure 4) and a wave gauge on buoy 46107 was deployed in MS. Buoys 46060, 46081, and 46107 were instrumented with a downward looking RDI 150 KHz Workhorse Acoustic Doppler Current Profiler (ADCP), and a Seabird Microcat suspended from a cage. The NDBC processes and posts the ADCP and CTD data from the surface buoys in near real time on the data buoy web site (http://www.ndbc.noaa.gov). Concurrent with this effort an additional weather buoy was deployed off Montague Island's Cape Cleare 46076 bringing the total array for PWS and the adjacent GOA to 5 automated data buoys. Buoy 46060 went adrift in the spring of 2010 and stranded. In the process the in-water sensors were lost.

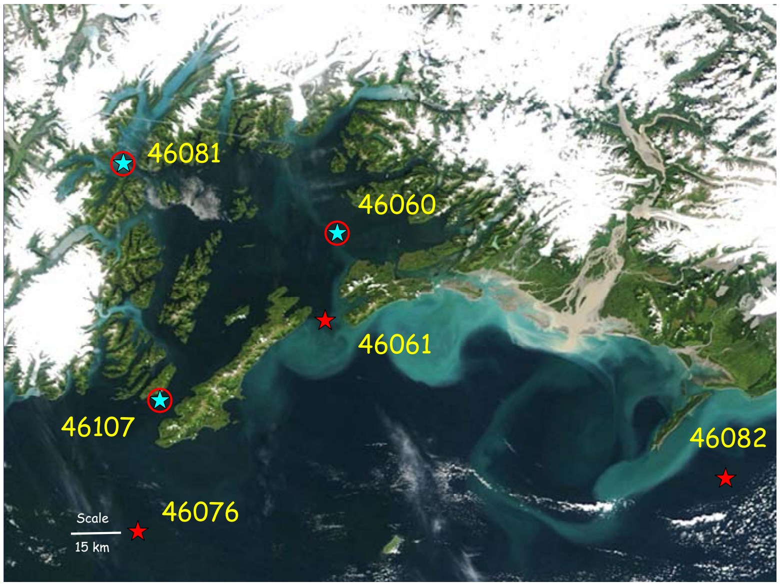


Fig. 6. Locations of NDBC data buoys in PWS and adjacent GOA. Circled blue symbols indicate the buoys upgraded with in-water sensors.

Oceanography: Circulation and water exchange processes

PWS and the adjacent shelf support a wide variety of producer and consumer species, including sea birds, marine mammals, and commercially important fish stocks. Understanding the linkages between the physical and biological components of this tremendously productive ecosystem is necessary for a better understanding of the physical processes that control a biological response and for effective management of marine resources. The Sound Ecosystem Assessment program (1994-1999), funded by the Exxon Valdez Oil Spill Trustee Council, identified exchange between the northern GOA and PWS as one of three physical processes that exert the most influence on the biology of phytoplankton, zooplankton, and juvenile fish within the Sound (Vaughn et al., 2001). An accurate description of the flow through HE is therefore necessary to investigate the relationship between circulation variability and biological variability in PWS. Observations (Muench and Schmidt, 1975; Niebauer et al., 1994; Vaughn and Gay, 2002) and numerical simulations (Bang and Mooers, 2003) show cross-channel variations in HE hydrographic and velocity fields. In spite of this spatial variability, all current meter mooring programs investigating flow through HE prior to the PWSOS were comprised of single-site moorings unable to resolve horizontal or across-channel variability. Furthermore, none of these earlier mooring programs measured flow in the upper 20-40 m of the water column.

The PWSOS current meter mooring project addressed these two significant limitations to acquiring an accurate description of transport variability through HE and MS. The goal of the mooring program was to quantify the interannual variability of exchange between the Gulf of Alaska and PWS. Two subsurface current meter moorings were deployed across HE and MS to complement the NDBC buoys (Figure 5).

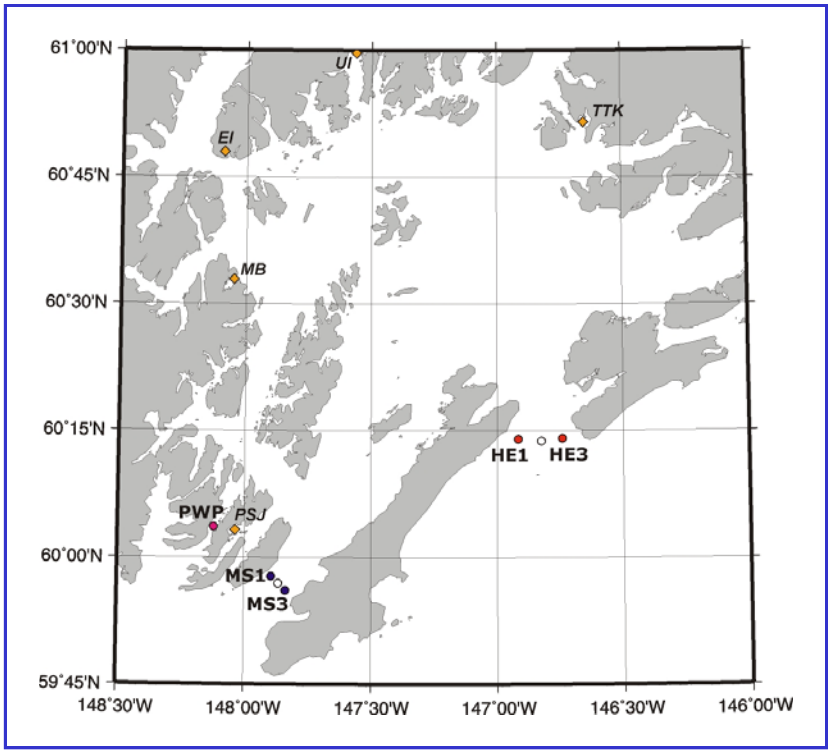


Fig. 7. The locations for mooring arrays in the major entrances to PWS are shown at HE 1 and 3, and MS 1 and 3.

Each subsurface mooring had two RDI 300 kHz Workhorse ADCPs at ~100 m depth, one upward-looking and one downward-looking (Figure 6). All ADCPs acquired measurements of current speed and direction at 15 minute intervals. Each of the subsurface moorings had conductivity-temperature recorders (CTDs) mounted at 30 m, 100 m, and 5 m above the bottom. These instruments periodically sampled temperature and salinity and thus tracked changes in water properties over time. Used in conjunction with the ADCP current measurements, they help identify periods of deep water exchange (which tends to be colder and saltier) into PWS. These moorings were discontinued in the spring of 2010.

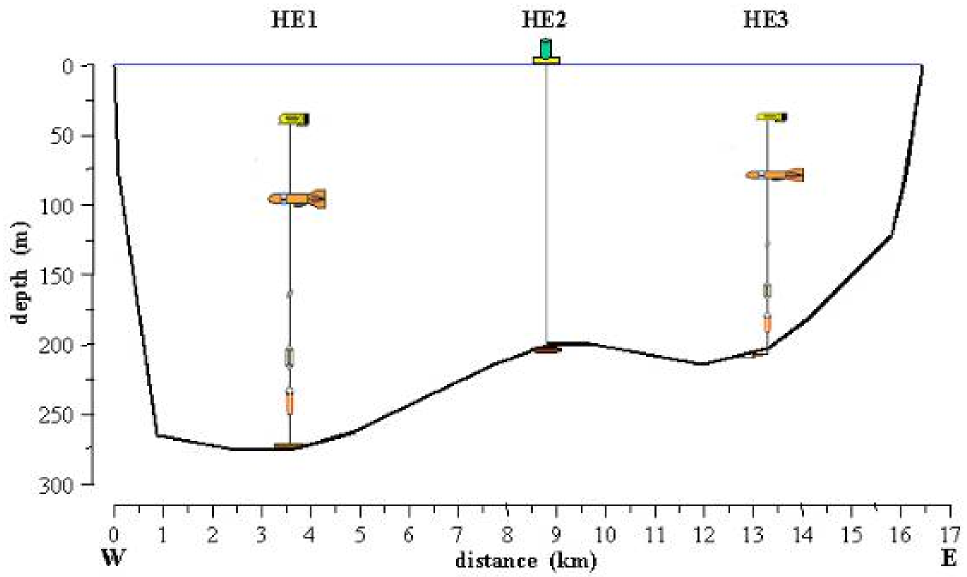


Fig. 8. Basic design of the oceanographic moorings. HE2 is the NBDC buoy. A similar arrangement was in place in Montague Strait.

Oceanography: Nearshore moorings

This project provides better information of the spatial and temporal variability of ocean water in the nearshore zones of PWS and provides near real-time water quality data for assimilation into the ROMS circulation model (see below). The data is also available for the NPZ (nitrate-phytoplankton-zooplankton) modelling effort and for hatchery management. The moorings were installed on existing oil spill response buoys (with permission from the Alyeska Pipeline Service Company) at Sawmill Bay, Esther Island, and Naked Island (Figure 7). The mooring instrumentation consisted of a Seabird SBE16 (pressure, temperature and salinity) and a Wetlabs ECO FLNTUSB (fluorescence and turbidity), cage-mounted at 5 meters depth, and the sampling interval was 10 minutes.

The moorings at Sawmill Bay and Esther Island were interfaced through a Campbell Scientific (CS) CR1000 data logger mounted on a buoy in a waterproof enclosure, which also contained batteries, power management hardware and a radio modem (CS RF401). A 20W solar panel and antenna were mounted on the buoy gantry to keep the batteries charged. Data were communicated via radio modem from the buoy to a Starband upload center located at nearby hatcheries. Data were archived on a CS Loggernet server maintained by Micro Specialties Inc., and made available to AOOS via the internet (http://ambcs.org/SiteViewer.shtml). The Naked Island mooring did not have communications and data was manually downloaded. These moorings were discontinued in the spring of 2010.

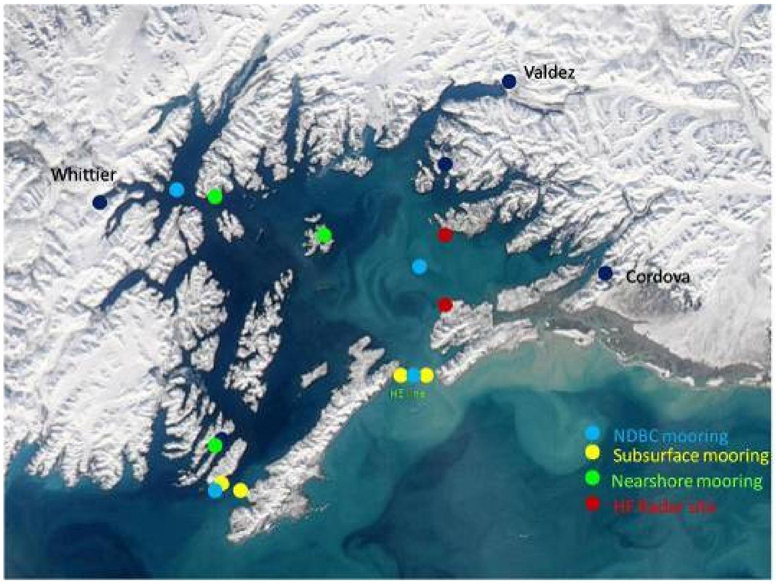


Fig. 9. Location of all moorings in the summer of 2009. The oceanographic moorings are represented by the yellow dots, nearshore moorings by green dots, and NDBC buoys by blue dots. Red dots are locations of radars.

<u>Oceanography: Deep water mooring (residence time)</u>

This project was to identify the magnitude and frequency of current flows that renew the waters in the deep basins of PWS. The immediate purpose for a mooring was to contribute data to ocean models to resolve bottom water circulation. The long-term goal of monitoring the renewal of bottom water was to better understand the forces driving food variability in PWS. *Neocalanus* copepods utilize the deep basins of PWS as an over wintering habitat. If mechanisms affecting the abundance of population in diapause and their offspring were known, then better predictions may be possible to explain spring time variability. The abundance of spring time copepods has been linked to the survival of emerging juvenile salmon, and therefore the eventual return of adult salmon that are a mainstay of the local economy. The mooring was to be deployed in the deepest portions of PWS (Figure 8). The mooring was design with three Seabird Microcats with one near the bottom above the anchor (>600 m), another mounted at approximately 200 m, and the third near the surface. This mooring was never deployed due to permitting issues and entanglement concerns from local fishers.

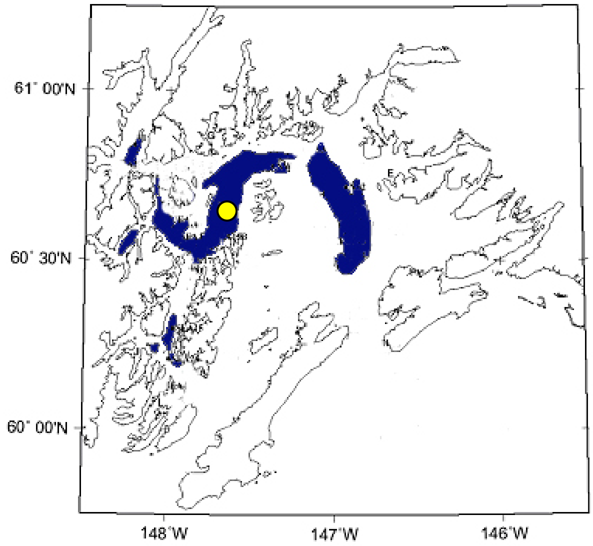


Fig. 10. Map of the Prince William Sound basins > 400 m deep are shown shaded. The solid circle indicated the proposed location for a mooring.

Oceanography: Copper River stream gauge

AOOS partnered with the U.S. Geological Survey (USGS) to deploy a stream gauge on the Copper River and communicate the data in near real-time to the internet. The USGS installed and maintains the gauge with funding provided by the State of Alaska. This instrument continuously measures the river discharge from the Copper River watershed (Figure 9) and allows for the assimilation of these data into the nested ROMS ocean circulation model (see below). The discharge from the Copper River is a significant source of fresh water to the Gulf of Alaska, and the resultant buoyancy forced current flows into PWS through HE and is thought to play a major role in driving the variability of circulation patterns. This real time data stream is vital for improved ocean circulation forecasts to better understand the relationship between fresh water sources and the circulation in PWS.

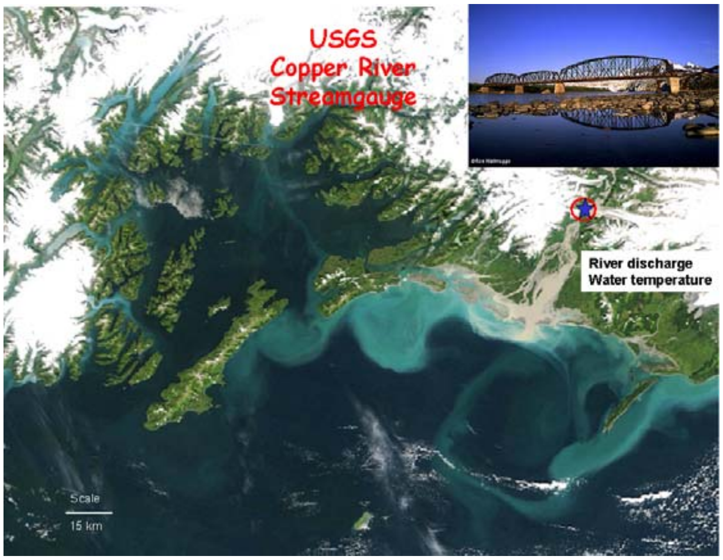


Fig. 11. Location of the Copper River stream gauge operated by the USGS.

Oceanography: Surface Current Mapping

The UAF Salmon Project has deployed new High Frequency (HF) Radar instrumentation in PWS at Shelter Bay and at Knowles Head (Figure 10) to provide real time surface currents of the central basin. These surface current mappers (SCMs) are instruments manufactured by CODAR Ocean Sensors in Los Altos, California. The funding for these systems is being provided by grants awarded by The National Aeronautical and Space Administration (NASA) and The National Oceanic and Atmospheric Administration (NOAA).

A single CODAR (Coastal Ocean Dynamic Applications Radar) site consists of two antennae, a transmit antenna and a receive antenna. The antennae are separated by about 30 meters. A single site measures radial currents by transmitting a radio signal at a specific frequency out over the surface of the ocean. The radio waves scatter off of the waves on the surface of the ocean, and some are then recorded by the receive antenna. These backscattered radio waves are then used to compute currents moving toward or away from the site. Two sites, in close proximity to one another complement each other in such a way that total surface currents over their region of overlap are computed. A challenging aspect of operating these systems from remote locations in Alaska is that power and telecommunication lines are often miles away. Therefore the surface current mapper systems in PWS are self-contained, using a diesel generator for power and satellite uplink for communication (Figure 11).

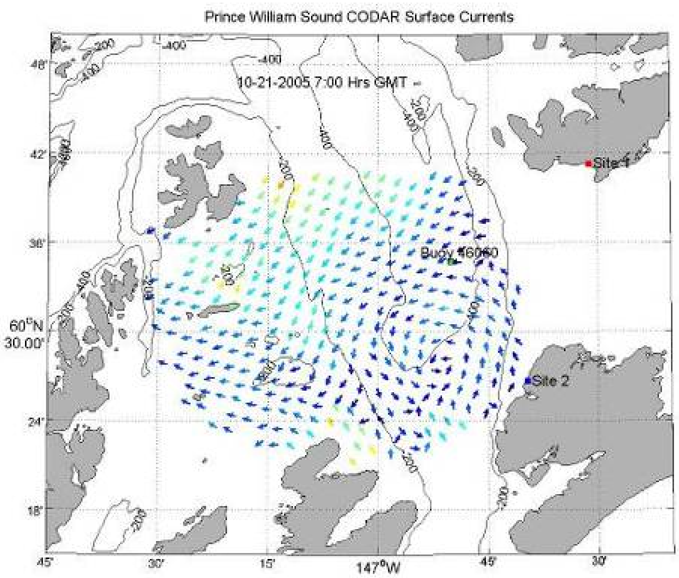


Fig. 12. A sample of the surface current field as determined from the HF radar installations at Knowles Bay (site 1) and Shelter Bay (site 2).

Fig. 13. HF radar as deployed in Prince William Sound.

Oceanography: Thermosalinograph/fluorescence surveys

Fresh-water (buoyancy) inputs to PWS and Alaskan coastal waters from rivers and glaciers have strong impacts on coastal circulation and thermohaline properties. Periodic surface salinity mapping quantified this very important buoyancy forcing component on ocean circulation. A flow-through thermosalinograph and fluorometer was installed on a high speed fishing vessel (Alena K) to conduct spatially comprehensive surveys of the surface waters in PWS. Surveys were conducted on a monthly basis from April through November and additional surveys were conducted as weather permitted in the winter. Consistent track lines were followed during each survey so that direct comparisons among datasets could be made (Figure 12). The vessel stopped periodically to profile the water column to quantify vertical variations. The same vessel was contracted on an annual basis for the duration of the monitoring period to avoid transferring equipment. At the end of each survey, the data was downloaded from the instruments and maps produced. These data were made available on the AOOS web site for assimilation into the nested ROMS model. See Okkonen and Belanger (2008) for results of this project.

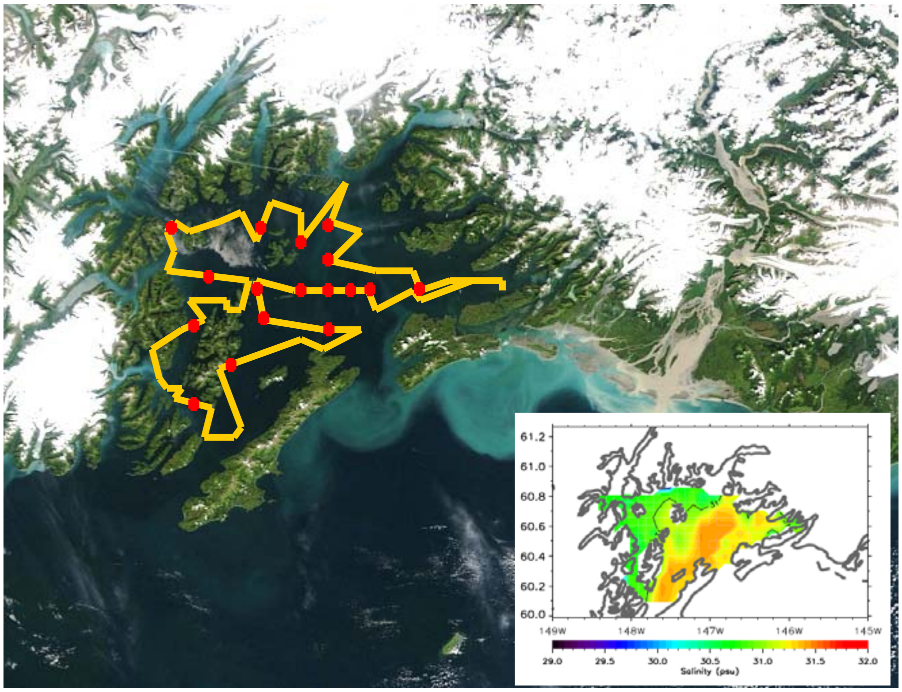


Fig. 14. Survey track lines and salinity map produced from the dataset.

Oceanography: Biophysical coupling

The central overarching ecological hypothesis for PWS is that both the degree and source of connectivity of PWS to neighboring coastal marine systems combined with natural and anthropogenic disturbances drive dramatic variation in ecosystem processes, community structure, and population dynamics over space and time. Of particular interest for understanding predominant causes of ecological variability is the relationship of water flow through the major entrance of PWS and the advection of nutrients and plankton. AOOS funded the purchase of additional sensors to enhance moored buoys in HE and MS to measure nitrate concentrations, phytoplankton chlorophyll fluorescence, and copepods and euphausid zooplankton (Figure 13). The funds for ISUS nitrate sensors and Tracor multifrequency plankton sensors were budgeted but reallocated to fund repairs and replacement instruments for the HE and MS moorings. Chlorophyll fluorometers were purchased but not deployed in HE or MS.

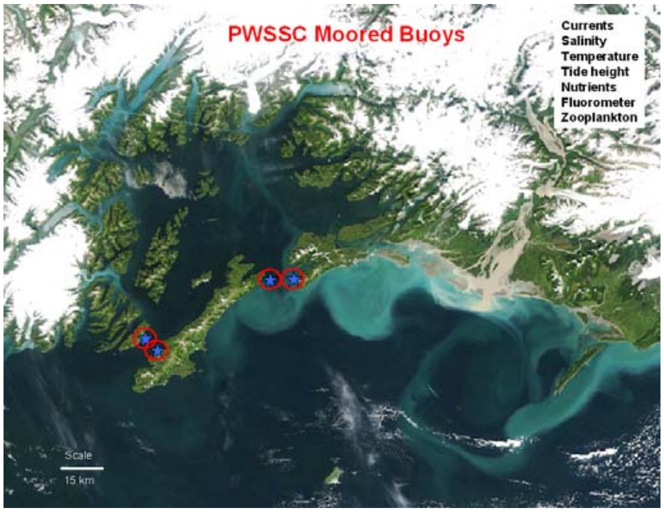


Fig. 15. Locations of moored buoys in HE and MS.

Modeling Components

Weather forecasts

The PWS Observing System provides for many weather observations within a relatively small area. With over 20 weather stations reporting real time data within an area of 10,000 square km, PWS has one of the densest networks of marine and terrestrial weather observation platforms in the world. Using these data, the AEFF operates weather models for PWS that have much finer resolution than the current NWS model. Where the NWS now only has forecasts for areas of about 40 km, the models developed by AEFF allow for forecasts of areas as small as 4 km.

The Weather Research and Forecasting (WRF) system is now being primarily used for the atmospheric modeling in PWS and is compatible with NWS requirements. The WRF modeling system is intended to be a next-generation mesoscale assimilation and numerical model system. The model is in continuing development by a group of agencies including NCAR, NOAA, DOD AFWA, FAA, University of Oklahoma, and others. The North American Mesoscale WRF (NAM-WRF) is currently one of the main workhorse models for the National Centers for Environmental Prediction (NCEP). The NAM-WRF is run at 45-km horizontal grid-point spacing. The AEFF runs the WRF model twice per day, initializing at 12 and 0 Z, on a local computing cluster and on the supercomputer at the Alaska Regional Supercomputer Center. Comparisons between model forecasts and point observations are now being analyzed.

The atmospheric circulation model forecasts drive the ocean and wave models. Thus the quality of the meteorological forecasts is important as it influences the output of these downstream models. OSRI, AOOS, and the Cook Inlet Regional Citizens' Advisory Council are funding the operations and limited development of the WRF model through 2010. Figure 14 illustrates a forecast map of surface wind velocity and direction.

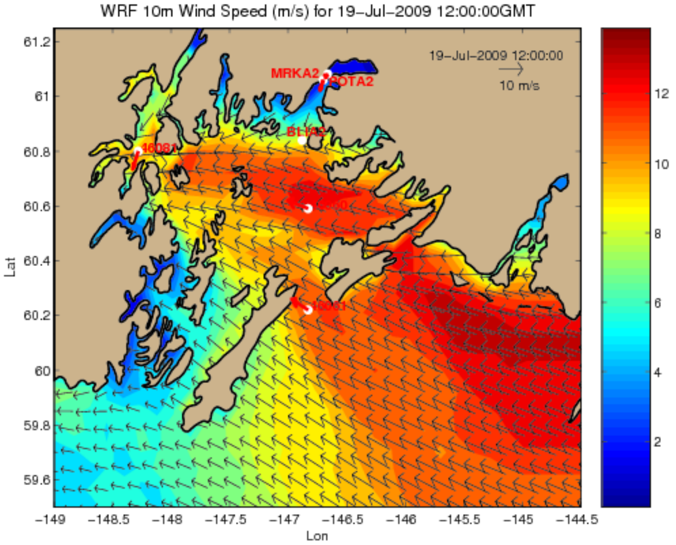


Fig. 16. Example output from WRF for July 19, 2009.

Wave forecasts

Wave simulations in the Gulf of Alaska now generate relatively coarse scale forecasts that are of little value at the scale of PWS. Using SWAN (Simulating WAves in the Nearshore) modeling in PWS allows for forecasts at finer scales that are accurate to within 500 meters. The SWAN model was developed in Holland and is being used in more than 50 countries to predict wave heights in nearshore and inland waters. It has been used to accurately predict waves in the Gulf of Maine for nearly two years.

Surface waves constitute an extremely energetic component of the physical oceanography affecting coastal Alaska. Waves create turbulent effects that can be orders of magnitude larger than baroclinic currents and that can overwhelm them to the extent that even the identity of the currents can periodically be destroyed. From a practical standpoint, information about the wave conditions in the Alaskan coastal areas is needed to assess the fate of oil spills and related recovery efforts and safe boat/ship operations. Because buoy and satellite altimeter measurements of waves in coastal waters suffer from spatial and/or temporal sampling limitations, grid-based wave modeling using SWAN is being developed for PWS by Texas A&M University (TAMU) to make wave predictions for both oil spill response and marine safety applications. TAMU is using satellite and in situ wave observations for validation of model results and satellite wind and wave observations for data assimilation to enhance model results. Besides traditional data assimilation schemes, TAMU will explore techniques of artificial intelligence for forecasting and correlation (Londhe and Panchang, 2006; 2007). Efforts to include satellite measurements, in addition to buoy data, have been made by Singhal et al. (2010) who have conducted a detailed assessment of the forecast skill. This provides the end-user with a measure of the uncertainty associated with a specific forecast.

The SWAN model uses data collected from the three NDBC buoys for validation in PWS, as well as the Cape Suckling and Cape Cleare buoys to validate Gulf of Alaska waves (Singhal and Panchang, 2009). The model runs every 24 hours to track and predict wave heights. In addition, new technology is being developed by the research group at TAMU that will allow for real-time wave forecasts that are nearly exact for up to six hours at a time. Once it is fully developed, this technology can easily be added to the SWAN modeling system.

Hourly observations are compared with nearest model grid points. Along with straight-up run-by-run comparisons of predicted vs observed fields of wind speed, direction, temperature and pressure, accumulated RMSE and bias are computed for each selected station. The results demonstrated the modeling scheme's ability to predict such events with reasonable accuracy (Singhal et al. 2010). Accurately forecasting waves could help researchers determine the importance of waves in sediment transfer, and especially how the movement of sediments affects marine life around the Sound. Figure 15 illustrates a wave forecast output from SWAN.

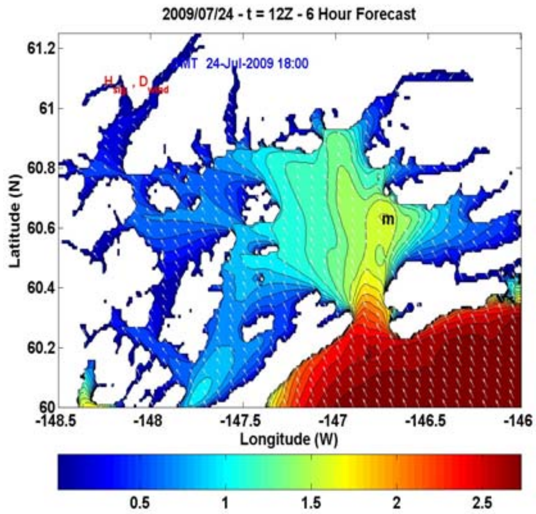


Fig. 17. An example output from SWAN for July 24, 2009.

Oceanic circulation forecasts

In September 2004, UCLA and JPL ocean labs were asked to design a numerical framework to help advance the knowledge of PWS ocean dynamics. Ocean circulation forecasts and error estimates are based upon a nested series of spatial domain models using the Regional Ocean Modeling System (ROMS). ROMS uses a terrain-following vertical coordinate and represents the current state-of-the-art. Specifically, UCLA's responsibility was to build a PWS configuration of ROMS nesting capability. Three nested grids were generated with a mesh size of 10, 3.3 and 1.1 km encompassing respectively the whole Gulf of Alaska, the central coast of Alaska and PWS (Figure 16).

The circulation in the Sound is driven by an intricate mixture of buoyancy, wind, tidal and remote forcing. The eddy present in the central part of the Sound during most of summer 2004 is also a robust feature in the model even when forced by climatological monthly winds and in the absence of fresh water inputs. The mechanisms responsible for the occurrence of this eddy will be investigated. Also, the structure of the currents across Hinchinbrook Entrance shows strong baroclinicity and temporal variability in relation to the mesoscale activity present outside PWS on the slope. Despite these challenging features, the ROMS implementation for the PWS and the nearby Gulf of Alaska coastal oceans shows very encouraging preliminary results when compared to observational data from moorings and drifters.

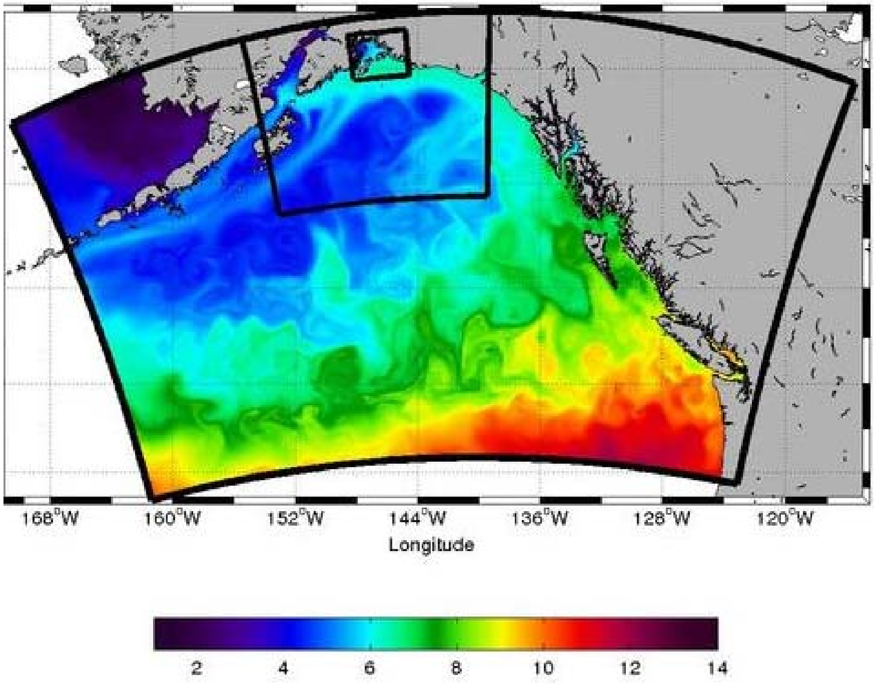


Fig. 18. Three-domain nested ROMS configuration for the PWS modeling, data assimilation and nowcast/forecast system.

Data assimilation

A major goal of the observing system in PWS is to develop an operational system that delivers information on physical and biological conditions in real-time to research and application users. This information includes raw data on environmental conditions, such as wind velocity, air temperature, precipitation, ocean currents, water level, ocean temperature, tides, and salinity, and modeled forecast conditions. A significant new feature of ROMS implemented at JPL is the 3-dimensional variational (3DVAR) data assimilation system. This allows ingestion of real-time data for validation and correction of model nowcasts and improved model forecasts.

NPZ forecasts

An ecosystem model was developed based on the nested ROMS domains. The long-term modeling goal for this project is to establish coupled circulation-ecosystem models that are capable of producing real-time and forecasts of nutrients, plankton, and marine habitat for key fisheries for the PWS and northern Gulf of Alaska. The ecosystem model for PWS is based upon the CoSINE (Carbon, Si(OH)$_4$, Nitrogen Ecosystem) ecosystem model. The CoSINE model has been applied to North Pacific, the equatorial Pacific, and the California coastal upwelling system. The CoSINE model includes silicate, nitrate and ammonium, two phytoplankton groups, two zooplankton grazers, two detrital pools, TCO$_2$ and recently oxygen has been added to constrain remineralization processes in the model. Below the euphotic zone, sinking particulate organic matter is converted to inorganic nutrients by a regeneration process, in which organic matter decays to ammonium and then is nitrified to NO$_3$. Incorporating oxygen into the ecosystem model adds extra constraints on the treatment of regeneration processes in the model, and there are many dissolved oxygen measurements for the PWS. Silicate regeneration is modeled through a similar approach but with a deeper regeneration depth profile, which reflects the tendency of biogenic silica to have higher preservation efficiency compared to other particulate organic matter.

Data Management

The data management and modeling group (DMAG) of AOOS provided several areas of expertise and support for the PWS demonstration including data transport, analysis, visualization, modeling and data archive.

Table 1. AOOS 5-Year Budget

Program	Annual Funding by Organization														Funding Summary					
	2005			2006		2007		2008			2009				Organization Totals					Component Total
Observing System	OSRI	PWSSC	AOOS	OSRI	AOOS	OSRI	AOOS	OSRI	AOOS	NASA	OSRI	RCAC*	AOOS	NASA	OSRI	PWSSC	RCAC*	AOOS	NASA	
Snotel	40	95	90	40		40		40			40				200	95		90		385
NDBC upgrades		128													0	128		0		128
Nearshore Moorings									50				53		0	0		103		103
HE & MS Moorings	120	600	40	120	95	120	30	120			120				600	600		165		1365
Stream guage			10												0	0		10		10
Thermosalinograph			10												0	0		10		10
Hydrographic surveys	20			20		40		40			40				160	0		0		160
HF radar			147		147		147		75				132		0	0		648		648
WRF	60			60		60			10		50		10		230	0		20		250
SWAN		100							10			15	10		0	100	15	20		135
ROMS	60	300		60	50	60	200		100				100		180	300		450		930
NPZ					100		100		20				20		0	0		240		240
Biological sampling					25		40								0	0		65		65
Vessel charter			20		25		42		35			20	50		0	0	20	172		192
Data analysis			18		33		30		42				56		0			179		179
Data management	20		**	20	**	20	**	20		**	20		**		100			**		100
Coordination	10		12	10	12	10	12	10	24		10		24		50	0		84		134
Field Experiment																				0
FE Coordination										38	50			33					121	121
Drifters								18		17	25			26	43				43	86
REMUS AUV											25		15					40		40
Slocum glider											20							20		20
Biological sampling											50									50
Satellite Imagery										52				57					109	109
SAROPS										20				40					60	60
Totals	290	1128	257	290	487	310	601	208	366	127	410	35	470	156	1363	1128	35	2226	333	5135

*Prince William Sound Regional Citizens' Advisory Council: some or all of this funding was prior to 2009

**AOOS funds for a data management program at UAF are not included here

Table 2. Summary of data reported from remote instruments.

			Data reported (%)					
Component	**Station**	**Variable**	**2005**	**2006**	**2007**	**2008**	**2009**	**Overall**
Snotel Weather	San Juan	temp	85	100	100	100	100	97
		wind	85	100	100	99	100	97
		solar	85	100	100	100	100	97
		precip	100	100	100	100	100	100
		press	85	100	100	100	100	97
	Esther	temp	100	100	100	100	100	100
		wind	100	100	99	98	99	99
		solar	100	100	100	100	100	100
		precip	10	100	100	100	100	82
		press	100	100	100	100	100	100
	Tatitlek	temp	21	100	100	100	100	84
		wind	21	100	100	99	98	83
		solar	21	100	100	100	100	84
		precip	21	100	100	100	100	84
		press	21	100	100	100	100	84
	Seal	temp	100	72	100	100	100	94
		wind	100	72	100	100	100	94
		solar	100	0	100	100	100	80
		precip	100	72	100	100	100	94
		press	100	72	100	100	100	94
	Nuchek	temp	100	99	100	100	46	89
		wind	100	99	100	83	31	83
		solar	100	99	100	100	46	89
		precip	100	99	100	100	46	89
		press	100	99	100	100	46	89
	Strawberry	temp		0	93	100	100	73
		wind		100	100	99	48	87
		solar		100	100	100	100	100
		precip		100	100	100	100	100
		press		100	100	100	100	100
	Mt Eyak	temp	100	95	100	100	100	99
		wind	100	93	99	95	99	97
		solar	100	95	100	100	100	99
		precip	100	95	100	100	100	99
		press	100	95	100	100	100	99
	Sugarloaf	temp			33	98	100	77
		wind			33	97	99	76
		solar			33	98	100	77
		precip			33	98	100	77
		press			33	98	100	77
NDBC Buoys	46081	temp	15	70	8	29	84	41
		salinity	16	73	8	29	84	42
		current	21	21	27	27	42	28
	46060	temp	99	24	0	0	0	24
		salinity	99	22	0	0	0	24
		current	25	0	19	23	22	18
	46061	temp		0	0	0	0	0
		salinity		0	0	0	0	0
		current		2	0	0	0	1
	46107	temp				0	0	0
		salinity				0	0	0
		current				23	8	16
Nearshore Moorings	San Juan	temp			11	79	73	54
		salinity			12	42	73	42
		chloro			12	84	73	56
		turbidity			11	79	73	54
	Esther	temp					56	56
		salinity					56	56
		chloro					73	73
		turbidity					56	56
	Naked	temp			Not telemetered			0
		salinity			Not telemetered			0
		chloro			Not telemetered			0
		turbidity			Not telemetered			0
	Tatitlek	temp			Not installed			0
		salinity			Not installed			0
		chloro			Not installed			0
		turbidity			Not installed			0
Deep Mooring	Central Sound	temp			Cancelled			0
		salinity			Cancelled			0
UAF HF Radar	Shelter Bay/Knowles Head	currents	0.0	1.2	0.0	0.0	0.1	0.3

Table 3. Costs for selected observing system assets. Initial capital cost and annual maintenance costs are shown. Cost per day of cumulative real time data received by year are listed (not including the year of deployment), i.e. for the SnoTel upgrade at Port San Juan, the initial capital cost was $10K and the annual maintenance costs are $4K, the data recovery is 100% and the cost per day decreases each year from $38 in 2006 to $18 per day in 2009.

			Budget			
	Initial	Annual	Cost/Cummulative # Data Days			
Station			2006	2007	2008	2009
San Juan	10000	4000	38	25	20	18
Strawberry	30000	4000	93	53	38	31
46081	40000	0	522	403	297	206
San Juan	30000	0		747	91	99
Shelter Bay/Knowles Head	0	147000	33562	67123	100685	122042

Sound Predictions 2009 Field Experiment

In July and August of 2009 a field experiment was conducted to quantitatively evaluate the forecasting skill of AOOS weather, wave, and ocean circulation models. We were particularly interested in evaluating how these models may enhance the performance of the General NOAA Oil Modeling Environment (GNOME) oil spill trajectory model and the US Coast Guard search and rescue model (SAROPS). Model performance evaluations were based on 1) retrospective analyses of historical observations and model output, 2) observational data collected during a two week field experiment in July and August 2009, and 3) comparisons with baseline performance during a similar experiment in 2004. The outcome of these analyses will help to evaluate the effectiveness of high resolution numerical models at different spatial scales and provide some guidelines on the utility and limitations of ocean observing systems in oil spill response and resource management.

During the field experiment, the fixed array of observing system instruments was augmented by thermosalinograph surveys and vessel-based measurements of pressure (depth), conductivity (salinity), temperature, chlorophyll fluorescence, turbidity, and nutrients along transects in the central basin (Figure 17). Also, nearly continuous measurements of temperature and salinity were collected using a Slocum glider and a REMUS-100 autonomous underwater vehicle (AUV). The AUV-based sampling provided continuous spatial and temporal data needed for data assimilation. Four types of drifting buoys were used to observe ocean circulation: A total of 44 drifters were repeatedly deployed, retrieved, and redeployed in the central basin during a 2-week period spanning spring and neap tides.

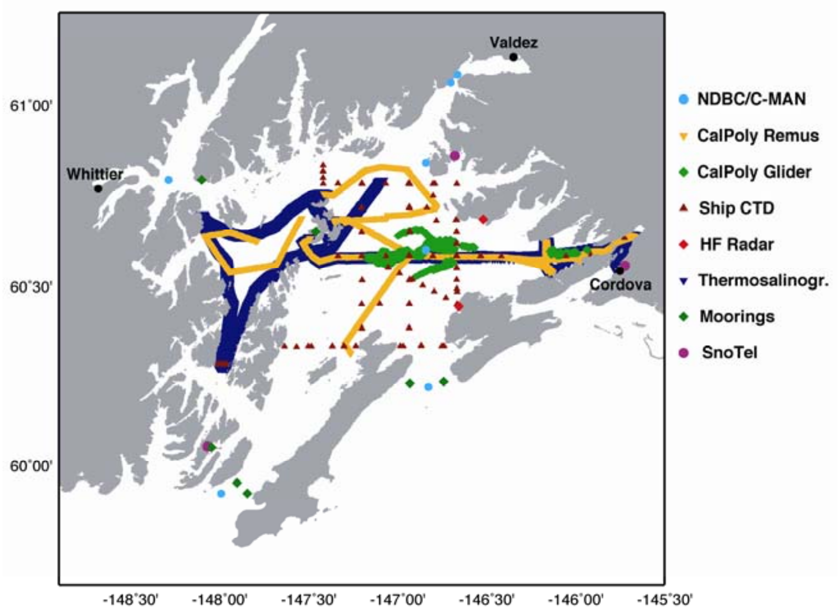


Fig. 19. Locations of in situ observational sensors and platforms during the 2-week long 2009 field experiment.

<u>Surface drifters</u>

The release and tracking of drifters was a key component of the 2004 Lagrangian Field Experiment (LFE). In 2004, two types of drifters were used: Argosphere drifters made by Metocean Data Systems and Surface Velocity Program (SVP) drifters made by Pacific Gyre. In 2009, four types of drifting buoys were used: the Argosphere and SVP drifters as in 2004, plus Microstar drifters made by Pacific Gyre, and the U.S. Coast Guard (USCG) Self Locating Data Marker Buoy (SLDMB) made by Metocean Data Systems. Drifting buoys were repeatedly deployed, retrieved, and redeployed during a 2-week period spanning spring and neap tides from July 20 to August 2. Model validation of surface and deeper currents in the central basin were emphasized and the majority of drifter deployments occurred within the domain of the HF radar surface current mapping system. Additional deployments occurred around the perimeter of the Sound to validate the velocity of surface currents forced predominantly by fresh water runoff from melting snow fields and glaciers.

The Argospheres are 28-cm diameter spherical buoys designed to track oil floating on the water (Figure 18). Position determination is through the Argos satellite system and a GPS receiver. For the GPS positions, an accuracy of +/- 10 m is normal. Position updates were obtained at 0.5-hour intervals. A hand-held tracking unit was used to provide location information in the field.

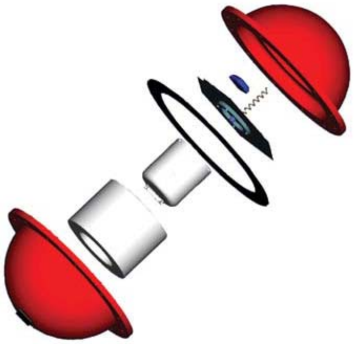


Fig. 20. Schematic of an Argosphere.

The SVP drifters are 38-cm diameter spherical buoys to which a drogue is attached, and they are expected to drift with the water at the depth of the center of the drogue. The drogue is a 2.5 meter long fabric tube suspended from the surface float and centered at either 10 m or 40 m (Figure 19). Both styles position with GPS receivers at either half-hourly (10-m) or ten minute (40-m) intervals. The 10-m units rely on Argos communication, while the 40-m units rely on Iridium communication. These drifters also use the Argos satellite system and a GPS receiver for location and tracking.

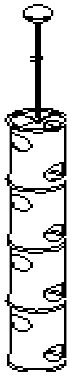


Fig. 21. SVP Drifter.

The Microstar drifters are designed to track the mean current at a depth of about 1 meter (Figure 20). The key elements of the drifter include the drogue, the surface float and the connecting tether. The drogue acts as a sea anchor locking the drifter to a parcel of water. The surface float contains the telemetry system, antenna, batteries and sensors.

Drifter positions are calculated by an onboard GPS receiver. Positions are transmitted to the user providing the information necessary to calculate mean current velocities.

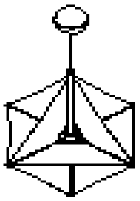


Fig. 22. Microstar Drifter.

The Metocean SLDMB (Figure 21) used by the USCG is designed specifically for deployment from a vessel or aircraft and for unattended operation during a 30-day lifetime. The SLDMB is accompanied by an onboard electronics package which includes GPS positioning. Service Argo, Inc, receives the data and forwards it to the NOAA polar-orbiting n-series satellites every 30 minutes. The data is subsequently transmitted to a secure USCG website for use by trained Search and Rescue Personnel. The USCG uses these drifters to construct current vectors from sequential SLDMB positions. In conjunction with the Search and Rescue Optimal Search Planning System (SAROPS) the USCG is able to establish the ocean surface motion and use this to better predict the motion of vessels and people during search and rescue operations.

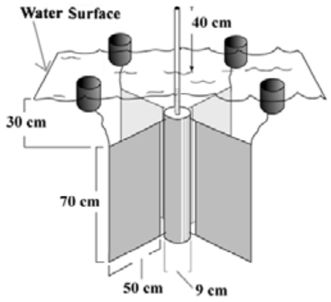


Fig. 23. U. S. Coast Guard SLDMB.

A Telonics hand held receiver was used to help guide the field recovery of the Argos drifters. The CLSAmerica Argos web tracking tool was used in concert to the extent that mobile phone communications are available. An Iridium receiver on the retrieval boat also helped guide the vessel to the drifters. Real-time telemetry through the Iridium network and displayed by UCSB was used to locate the 1-m microstar and 40-m SVP units.

During the main study periods the drifters were released at two sites: 60° 35'N 146° 56'W and 60° 47'N 146° 56'W. The drifters were deployed in two groups that contained at least three of each style of drifter except the 40-m drogued units, which were deployed only at the southern location.

The timing of the original deployments was scrapped because of the difficult weather encountered during the first few days; however, deployments were still generally made in the proposed locations. The field crew also made some effort to respond to deployment requests which differed from the original plan to address specialized questions.

Recovery of drifter buoys using Argos telemetry was particularly troublesome. The inefficiency was caused by the very limited range of the Telonics uplink receivers (only a few hundred meters). Additionally, the receivers were not capable of decoding an Argos data stream, so that obtaining precise GPS locations in real-time was essentially impossible. Iridium communications would be a significant improvement when the drifters are to be recovered from coastal areas.

Hydrographic surveys

In order to provide oceanographic information for the models to assimilate and to provide the data needed to validate the mixed layer depth, hydrographic surveys were conducted with a conductivity-temperature-depth (CTD) profiler. Similar measurements were also collected by autonomous underwater vehicles (AUV's). These ship based surveys also provided an opportunity to collect water for nutrient and plankton analysis, and bird and mammal observations.

The PWSSC SeaBird 19+ CTD measures pressure, conductivity, temperature, chlorophyll fluorescence, and turbidity. Depth, salinity and density (sigma-t) were derived from the measurements. A SUNA nitrate sensor was added to the CTD in order to provide validation data for the CoSINE NPZ ecosystem model. The data were processed at the end of each day to provide 1 m vertical binned information at each station. The data were transmitted to AOOS each evening by 2200 local time (ADST). ADST to ensure it was available for incorporation into the evening model run. A second

CTD that included an oxygen sensor and PAR sensor was borrowed to allow additional measurements to be collected from other smaller vessels. The drifter support vessel also had a CTD but with no additional sensors.

The primary survey areas included north-south (NS) lines and east-west lines in the central portion of the sound and east-west lines across Hinchinbrook Entrance (Figure 22). These lines all followed historical sampling stations. The main Hinchinbrook Entrance (HE) line spanning the Entrance at the location of the oceanographic moorings and also follows historical sampling locations but due to time constraints this line could not be sampled.

Additional surface hydrographic measurements were collected using a thermosalinograph from the AUV support vessel. Measurements included temperature, salinity, and position. The thermosalinograph system also included a chlorophyll-a fluorometer. There would have been more thermosalinograph data along the hydrographic transect lines if the dedicated hydrographic vessel instead of the AUV vessel had such a system. However, as it worked out, having the system on the AUV/drifter vessel meant that most of the thermosalinograph data came from drifter recoveries, which were generally found outside of the main hydrographic study area.

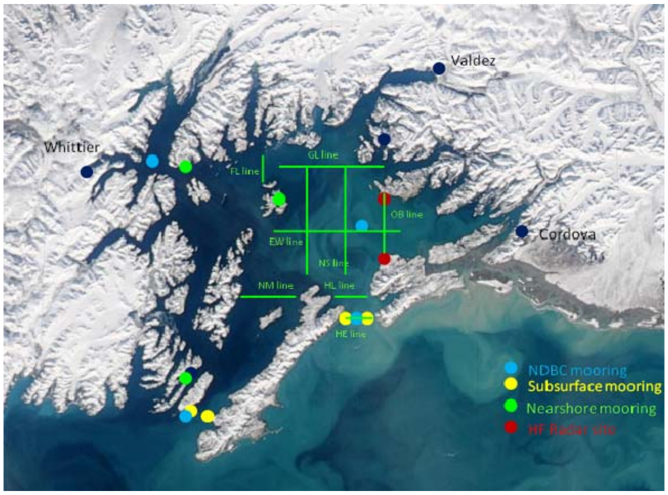


Fig. 24. CTD transect lines.

Autonomous Underwater Vehicle surveys

Nearly continuous measurements of temperature and salinity were collected using two autonomous underwater vehicles (AUVs). The first AUV was a Slocum glider (Figure 23)

Fig. 25. Glider being deployed by Cal Poly.

and the second a REMUS-100. The Slocum glider is a 1.8 m long torpedo-shaped winged vehicle built by Webb Research Corporation (WRC). It maneuvers through the ocean at a forward speed of 30-40 cm/s in a saw tooth gliding trajectory. The vehicle carries a range of high-quality scientific payloads including a Sea-Bird CTD and a WetLabs ECO-puck for chlorophyll and optical backscatter. The primary vehicle navigation system uses an on-board GPS receiver, with backup positioning and communications provided by an Argos transmitter. Two-way communication with the vehicle is maintained by RF modem or global satellite phone service via Iridium. The operating range using batteries is about 500 km with a maximum depth of 200 m. The vehicle provides data when it surfaces (approximately every 3 hours), which was sent to the modeling groups.

The Slocum glider was deployed on July 22nd and retrieved on August 2nd. The glider was deployed in the center section of PWS and operated along the center zonal transect starting south of Naked Island and ending north of the midpoint of Hawkins Island (Figure 24). The glider continued back and forth along this line for the duration of the experiment. The glider covered 250 km transiting this line and completed 1366 casts during this period. During the deployment, additional data collection was coordinated with Rutgers University providing them with salinity and temperatures of the surface layer (0-50 m depth) to assess water column structure (i.e. pycnoclines, mixed layer depths). These data were also fed to ocean model in collaboration with Yi Chao (JPL/UCLA) for real time data assimilation modeling efforts.

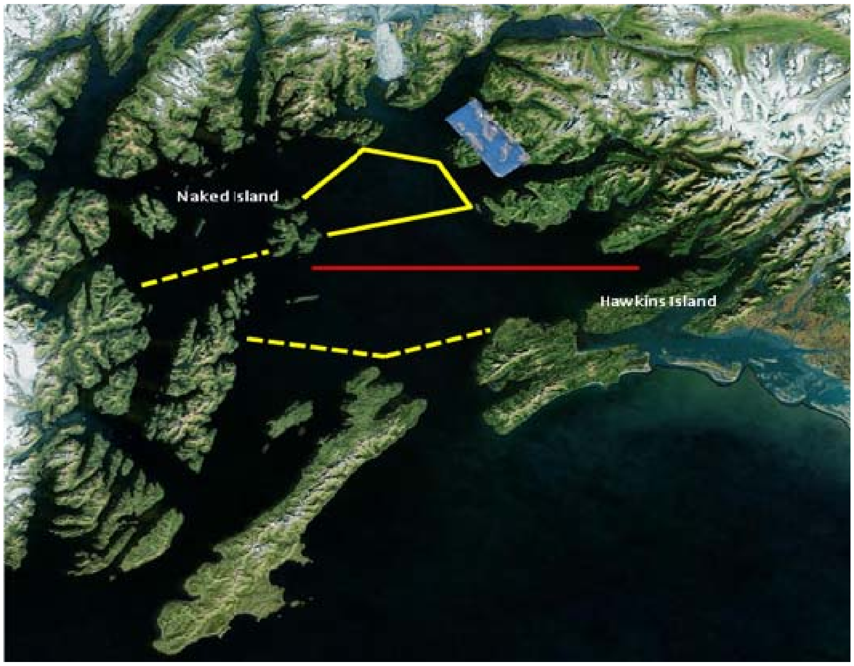


Fig. 26. Proposed transect lines for the glider (red) and REMUS (yellow) in Prince William Sound.

The REMUS-100 AUV used in this study was a propeller driven platform with a standard length of 160 cm, 19 cm in diameter, with a weight of 37 kg (Figure 25).

Fig. 27. REMUS-100 being deployed off the coast of California in 2007.

Background information on the vehicle and vehicle performance is detailed in Moline et al. (2005). The REMUS-100 has an autonomy of up to 80 km at 3 knots. It is equipped with a compass, headings sensors, a yaw-rate sensor, a control computer, an RD Instrument ADCP, and a Neal Brown CT sensor. This ADCP, a 1200-kHz Workhorse Navigator, has four upward and four downward looking transponder beams. Upward and downward looking beam arrays are used to measure current speed and direction in a range of user-specified depth bins above and below the vehicle. The vehicle incorporates the ADCP data to adjust for currents and calculate its position in real time while navigating. The downward looking array is also used as an altimeter, allowing for bottom tracking/mapping and fixed altitude flight. The conductivity and temperature data are collected at 2 Hz with a nominal vehicle speed of 1.7 m s^{-1}, yielding a horizontal data resolution of 0.85 m for the optical measurements. Although the REMUS-100 has many ways of navigation, the primary mode of navigation used the onboard compass with repeated surface GPS fixes approximately every 3 km. With this surfacing interval, the mean horizontal positional error is ~ 1%.

Through the study period of July 20th – Aug 2nd the REMUS-100 AUV was deployed 10 times. The vehicle covered over 475 km and completed over 500 sinusoidal profiles across PWS (Figure 26).

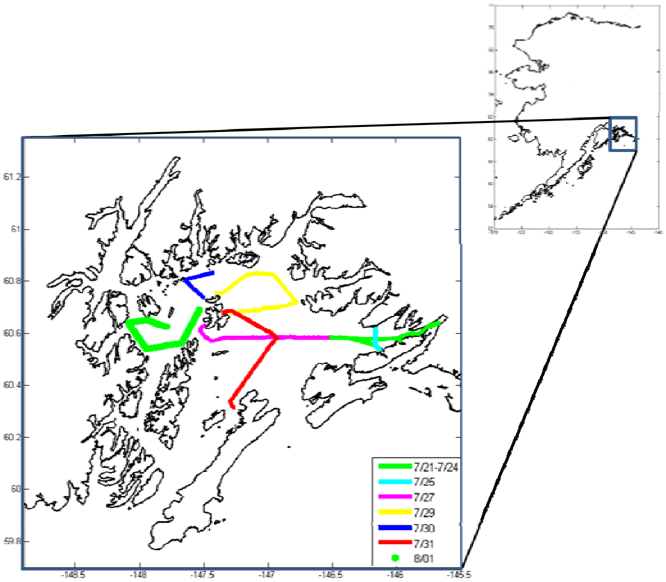


Fig. 28. AUV tracks in PWS from July 20 to August 2, 2009.

During these deployments, Cal Poly was responsible for launch and recovery. Observations from PWS included CTD, currents, and chl fluorescence. The AUV was deployed to provide a regional scale view of water column structure above 100 meters depth (i.e. pycnoclines, mixed layer depths) to help evaluate and improve the large scale performance of the model in collaboration with Yi Chao and Francois Colas (JPL/UCLA). Early missions from July 21st –July 25th concentrated on the eastern sound because of weather constraints on deployment. As weather improved on July 27th missions were run was run along the EW line and further into the Sound. On July 29th the REMUS-100 ran the original planned mission in the northern sound. July 30th's mission was run in the northern sound from Storey Island to Axel Lind Island to Glacier Island. July 30th's mission was run from Montague Island to EW4 to Naked Island as designated by the modelers. August 1st's mission was run in the western sound as designated by the modelers (thicker green line on figure). All of these later missions were directed by the ocean modeling team in an effort to collect data where the model was data sparse. The 500 profiles collected provided near real-time data on water column structure (i.e. pycnoclines, mixed layer depths).

AUV-based sampling proved to be an important component of the field experiment in being able to obtain continuous spatial and temporal data sets needed by the model for improving performance. AUVs also highlighted the degree of heterogeneity that traditional CTD casts could not reveal. As the study progressed, the modelers requested to have the REMUS run in specific areas to validate under sampled areas in the model. It was a success that the observational team with these platforms were able to successfully do this, however, it became very apparent that information on the expected range of salinities prior to deployment was important. Salinity could vary on the order of 10 PSU over the mission duration in certain areas, which drastically affected both AUVs ability to surface and communicate. We were fortunate that our mission end points were not overly influenced by this.

Biological sampling

A small biological sampling program was funded by OSRI and designed to provide observations to validate the nutrient-phytoplankton-zooplankton model. Profiling instruments added to the CTD measured oxygen concentrations, nitrate concentrations and *in situ* chlorophyll fluorescence. Dissolved oxygen concentration was measured with a SeaBird Electronics SBE43 oxygen sensor, and nitrate concentrations were measured with a Satlantic SUNA (Submersible Underwater Nitrate Analyzer). Chlorophyll fluorescence was measured using a WETLabs FLNTU and compared to extracted chlorophyll samples. Water samples were collected with a Niskin bottle for nutrient analysis (nitrate, phosphate and silicate), extracted chlorophyll, and CHN analysis. Samples were collected at six depths (surface, 5, 10, 15, 25 and 50 m) at every other station along the NS and EW transect lines. Similar samples had also been collected during a thermosalinograph survey in late-May and early-June.

Samples were filtered through a 0.7µm GF/F filter to remove particulates, and frozen on board for later analysis. The filters were retained for extracted chlorophyll analysis to empirically calibrate the *in situ* fluorometer. Similarly, nitrate samples were used to verify the observations made with the SUNA instrument. Nitrate, phosphate and silicate concentration were measured in the PWSSC lab with a Varian Cary 50 spectrophotometer and standard methods. Filters were also be retained for direct measurements of Carbon and Nitrogen content (i.e. CHN analysis) by The Water Center at the University of Washington.

The biological sampling also included net sampling (vertical tows) to measure mesozooplankton concentrations. Zooplankton concentrations were measured at three stations of the EW transect and plankton were collected using vertical tows using a 303 µm plankton net. Samples were preserved in formalin for later taxonomic analysis. Counts of identified species were converted to carbon content using the dry weights and dry weight to carbon conversions.

Weather forecasts

The WRF for PWS – hereafter referred to as PWS-WRF, is the modeling system based on WRF weather forecast model and implemented by the AEFF for use in the PWS - operated essentially as designed (Figure 27). The model was integrated forward in time using the results from the larger-scale 00Z NAM-WRF output fields as input (initial conditions and lateral boundary conditions) for the finer scale PWS-WRF. This part of the data flow— obtaining the larger (host) model data— went flawlessly for the duration of the FE. The smooth data acquisition allowed the AEFF to routinely begin integrating the forecast model by 2:30 Z each day of the FE, and the 48 hour forecast to finish before 6:00 Z on all but one day when the model run aborted on startup. Unfortunately, this error went undetected for several hours (an unfortunate reality of actually starting the model at 2:30 Z, 6:30 ADST, is that the run occurs after business hours). A confounding problem for this day was that communications between on-campus and off-campus sites was degraded, making external monitoring of the run impossible. Fortunately, this chain of events only occurred once during the FE and has not happened since.

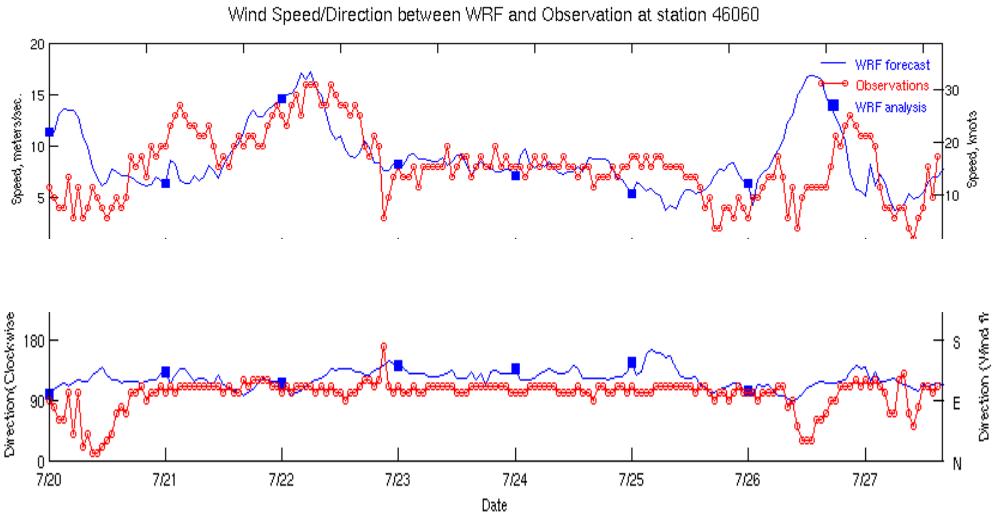


Fig. 29. Time series of the wind speed (top) and direction (bottom) at NOAA buoy 46060 during the 2-week field experiment as measured (red line) and predicted by WRF (blue square is nowcast and blue line is hourly forecast).

Wave forecasts

High-resolution simulations of significant wave heights (SWHs) using a state-of-the-art shallow water wave model SWAN were performed during the period of the field experiment. The wave forecasting system involved a three-tier coupled system - WAVEWATCH's simulations on a 30 km grid were used to force two other connected grids (at 2 km and 1 km resolution, respectively). The coarser grid covered the region from -149 W to -145 W and 59.25 N to 61.25 N which contained 201x101 grid points whereas the inner grid covered the region from -148.5 W to -146 W and 60 N to 61.25 N (251x126 points). Wind forcing was obtained from PWS-WRF model at a resolution of 4 km; the wind forecasts were provided by University of Alaska Anchorage (see above).

The wave forecasting system provided forecasts for SWH starting at 1200z every day for the next 36 hours.

For the most part, the protocol used above provided reasonable predictions for SWH during the field experiment (Figure 28). The quality of the wave forecasts, however, degraded for longer lead times. Some of the factors influencing the quality of SWHs could be directly attributed to the errors in the forcing functions (winds, boundary conditions), and the errors in the bathymetry. Future efforts will be geared towards minimizing these errors in order to provide the most accurate wave forecasts.

The proposed availability of PWS-WRF wind forecasts twice a day (at 0000z and at 1200z) helped the wave forecasting efforts. The wave forecasting system would, then, provide wave forecasts twice daily, replacing the previous wave forecast (at 00z) by the latest wave forecast (at 1200z). This should help minimize the errors in the wave forecast for all lead times by incorporation of latest wind-fields in the wave model. Secondly, using Stokes second order wave theory, estimates of surface wave-induced current velocities (Stokes drift) could be obtained. For the most part, the magnitudes of Stokes drift were larger than 20 cm/s during the period of the field experiment. In some cases, these estimates could be significant and should be accounted for in circulation and oil spill models.

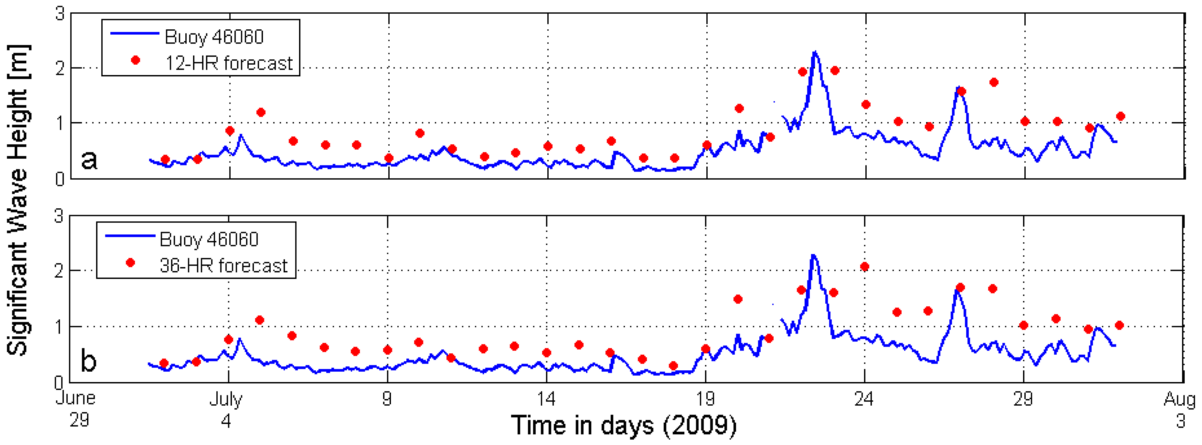


Fig. 30. Significant wave heights comparisons for a) 12-hour and b) 36-hour forecast from one station (NDBC buoy 46060) during the experiment period.

Ocean circulation forecasts

The funding for the UCLA modeling effort lasted only three years. Given the limited resources and the delay of the field experiment from 2007 to 2009, the UCLA funding was stopped in 2008, almost one year before the field experiment. This lack of modeling support limited the 2004 reanalysis and the associated model sensitivity studies.

The PWS circulation and variability were realistically forecasted during the field experiment provided that observational data was assimilated into ROMS. During the first week of the field experiment, the central sound was dominated by the easterly winds and northward surface current (Figure 29). The wind weakened during the second week of the field experiment (Figure 30) suggesting the formation of a cyclonic circulation in the center of the sound. By the end of the field experiment, the central sound circulation was characterized by a cyclonic (or counter-clockwise) eddy (Figure 31), which is very similar to that seen during the 2004 field experiment.

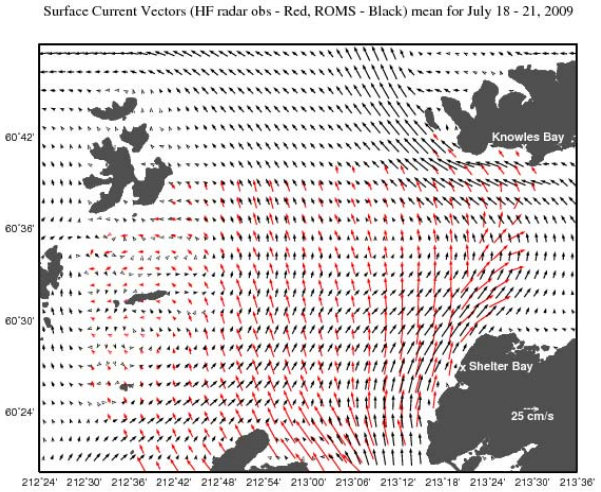
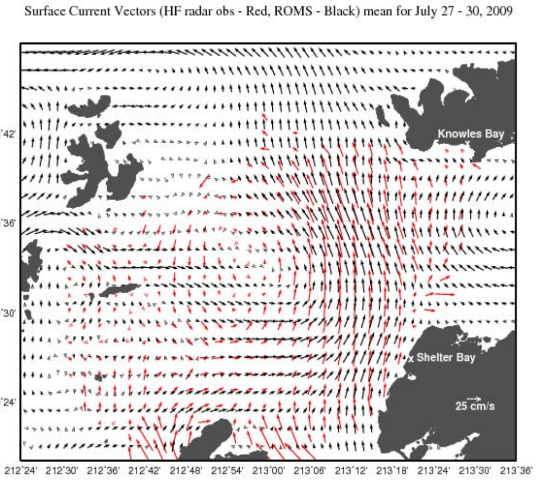
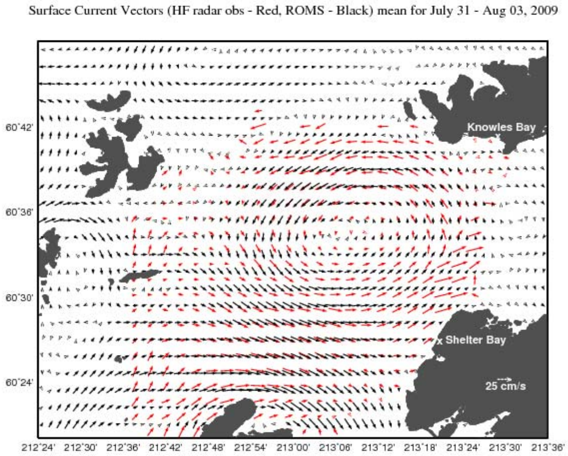

Surface Current Vectors (HF radar obs - Red, ROMS - Black) mean for July 18 - 21, 2009

Fig. 31. Surface current map as measured by the HF radar (red arrow) and predicted by the 3D ROMS circulation model (black arrow) during the first week of the field experiment (July 18 – 21).



Surface Current Vectors (HF radar obs - Red, ROMS - Black) mean for July 27 - 30, 2009

Fig. 32. Surface current map as measured by the HF radar (red arrow) and predicted by the 3D ROMS circulation model (black arrow) during the first week of the field experiment (July 27 – 30).



Surface Current Vectors (HF radar obs - Red, ROMS - Black) mean for July 31 - Aug 03, 2009

Fig. 33. Surface current map as measured by the HF radar (red arrow) and predicted by the 3D ROMS circulation model (black arrow) during the second week of the field experiment (July 31 – Aug 3).

The eddy present in the central part of the Sound during most of summer 2004 was also a robust feature in the model even when forced by climatological monthly winds and in the absence of fresh water inputs. A hydrological model was developed for PWS to route the precipitation over land to the appropriate river and coastal runoff locations. Figure 32 shows the Copper River fresh-water outflow estimated from the hydrological model. Compared with the available river gauge measurements this hydrological model prediction is quite reasonable.

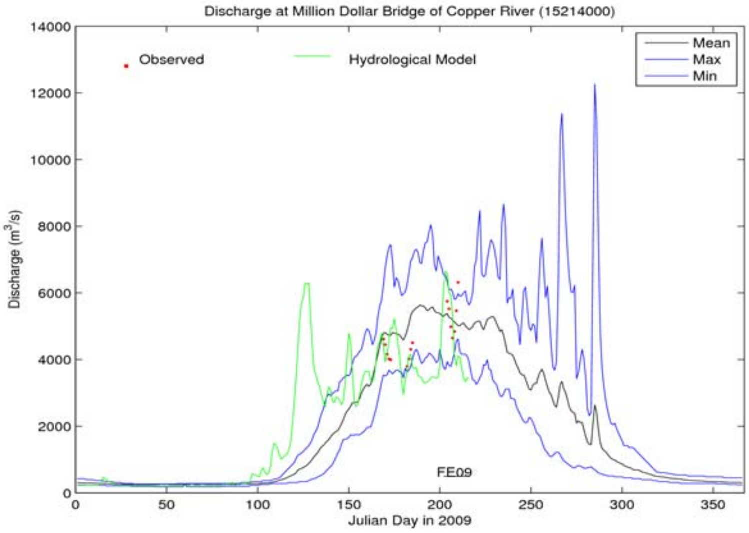


Fig. 34. Time series of the Copper River fresh-water outflow as measured by the river gauge (red dots) and the local hydrological model with precipitation from the WRF model. Black line shows the climatological mean with blue lines showing the extreme values. The green line shows the 2009 Copper River outflow.

The hourly ROMS forecast was used to predict drifter trajectories through a web-based interface that can be directly compared with the observed drifter trajectories (Figures 33 and 34). All the ROMS results are published through a user friendly web portal: http://ourocean.jpl.nasa.gov/PWS. During the field experiment, the vertical profile data of temperature and salinity from ship CTDs, gliders and REMUS AUV are also assimilated into ROMS (Figures 35 to 41). The ROMS nowcast was issued every six hours, and the 48-hour forecast was issued daily. By slightly varying the initial conditions, we had also issued ensemble forecast on the daily basis. Depending upon the computing resources, a typical 16 member ensemble was accomplished.

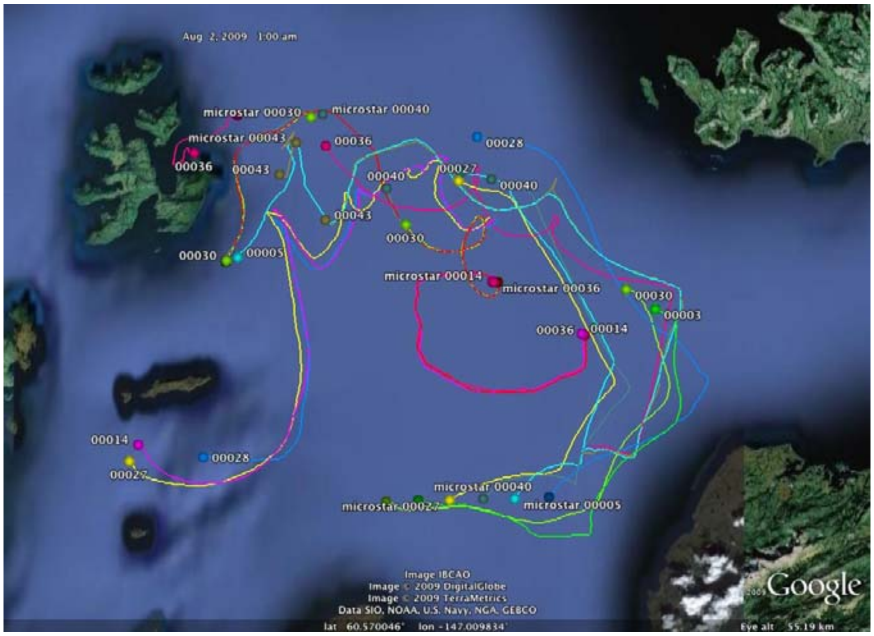


Fig. 35. All the trajectories recorded by the 12 Microstar drifters during the 2-week long 2009 field experiment.

Fig. 36. All the trajectories recorded by the 6 USCG drifters during the 2-week long 2009 field experiment.

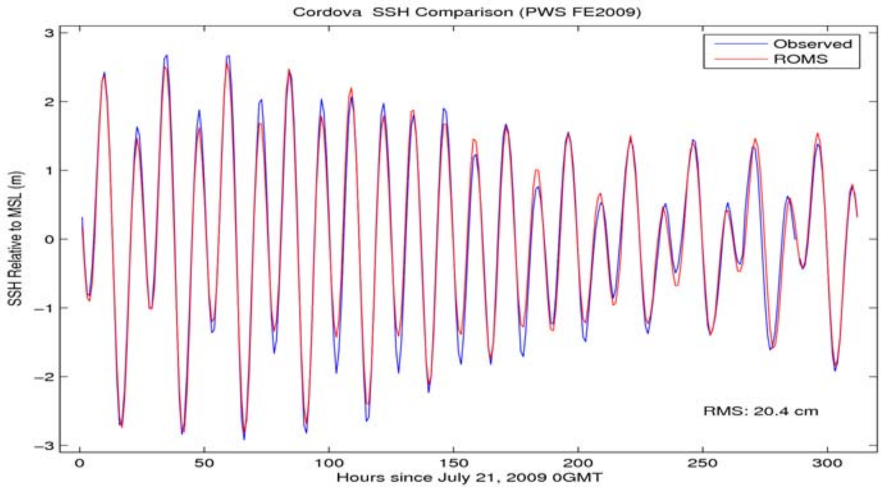


Fig. 37. Time series of the water level at Cordova as measured by the tide gauge station (blue line) and predicted by the ROMS model (red line). It shows the dominant 12-hourly M2 tides. The overall error of the ROMS model tidal water level forecast is about 20 cm, about 5~10% of the tidal amplitude.

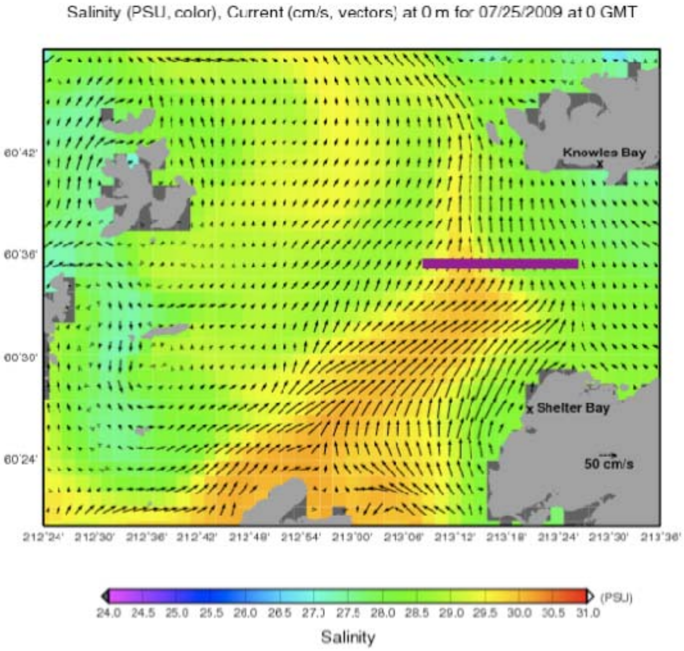


Fig. 38. Map of a ROMS predicted sea surface salinity on July 25 showing the northward flow and high salinity waters being advected into the PWS from the HE and MS.

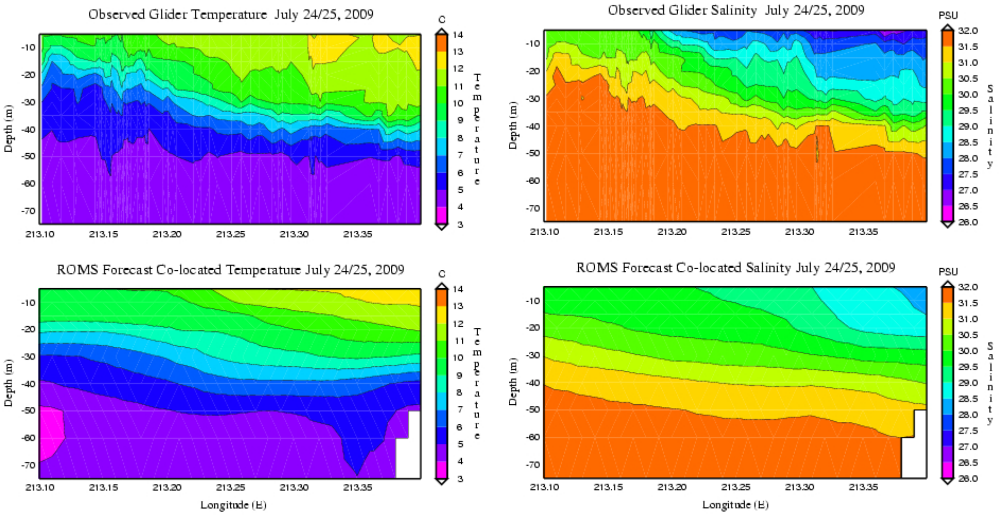


Fig. 39. East-west section (along the line shown in Fig. 5a) of the temperature (left) and salinity distributions as a function of depth as measured by the Slochum Glider (top) and predicted by the 3D ROMS model (bottom) during August 24-25.

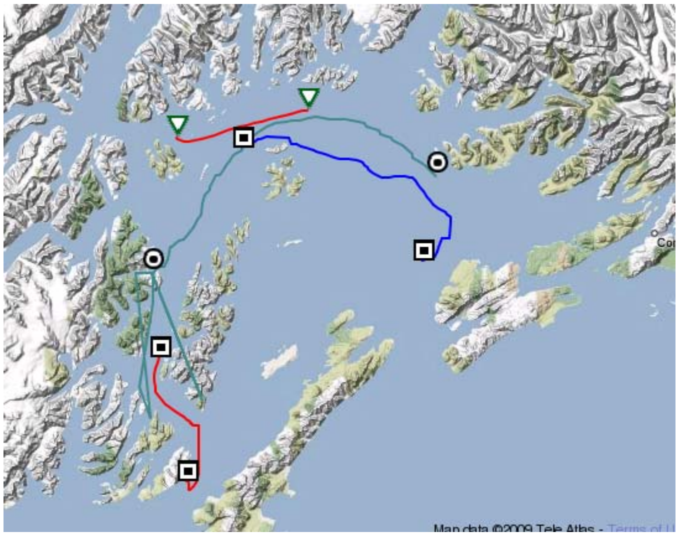


Fig. 40. A selected set of drifters during the first week of the field experiment showing a cyclonic (counter-clockwise) circulation within PWS.

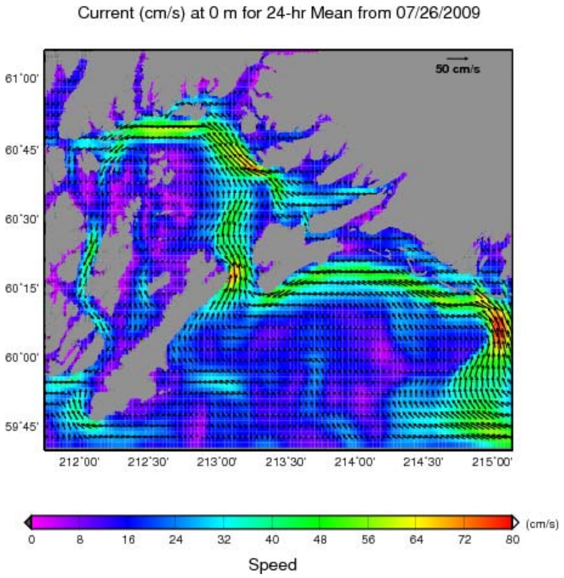


Fig. 41. Mean surface current map (with arrow representing direction and length and color contours representing speed) as predicted by the ROMS model on July 26 showing a consistent cyclonic circulation pattern as revealed by the drifter trajectories.

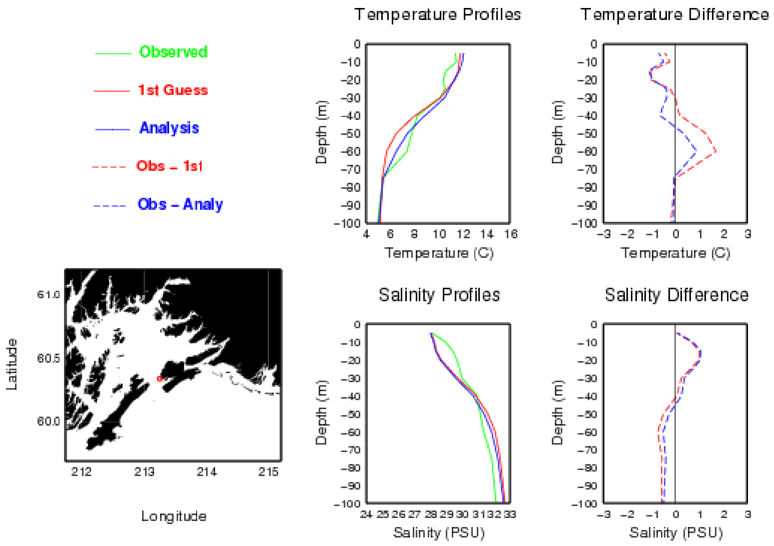


Fig. 42. Typical vertical profiles of temperature and salinity as measured by the ship CTD and predicted by ROMS on July 28. The error plots show the positive impact of assimilating this particular ship CTD data into ROMS.

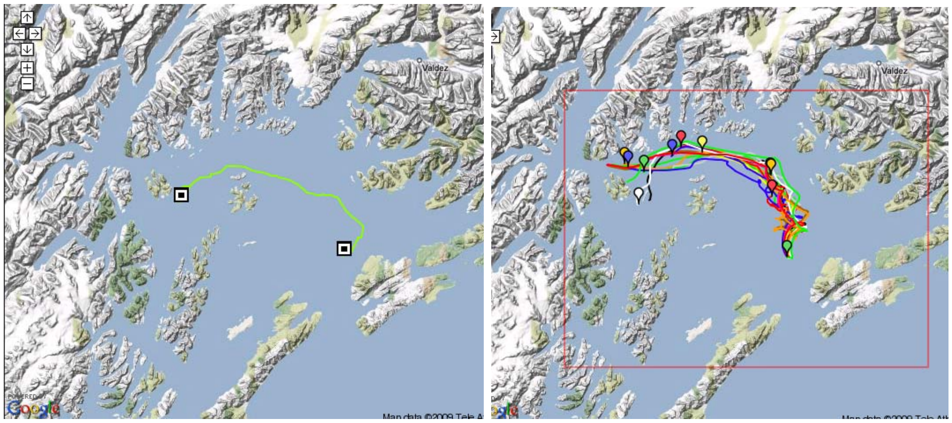


Fig. 43. Drifter trajectories as measured from the released time of July 25 at 02 GMT and recovered time of July 28 at 02 GMT (left panel) and predicted by a cluster of ensemble ROMS forecasts with slightly different initial conditions (right panel).

NPZ forecast

The initial efforts at ecosystem modeling were focused on simulating the seasonal variation of PWS and adjacent waters. To do this the ROMS-CoSINE model was forced by 2004 conditions. To overcome the scarcity of observational data, World Ocean Data from these regions was used for model validation with 5 domains (Figure 42) selected for comparison between model forecasts and WOD data. PWS (Domain 1) and Seward Line (Domain 3) have a relative dense data set, and were the focus of our model data comparison. In PWS, the model produced a reasonable seasonal cycle of temperature, salinity and chlorophyll (Figure 43). Chlorophyll climatology data shows a phytoplankton bloom in spring and a relatively smaller fall bloom due to weakening vertical stratification in fall, thus nutrient repletion, and high chlorophyll concentration. The modeled chlorophyll in PWS was very much comparable with WOD data set and remote sensing chlorophyll, although the model fall bloom was not as pronounced as the data. The modeled nutrients (nitrate, phosphate and silicate) concentration in PWS was relatively low compared with the WOD data especially during the winter months. The modeled nutrient concentrations on the Seward Line inner domain (Figure 44) was much better simulated, and its winter concentration was reasonably high. Both data and modeled chlorophyll shows a fall bloom. Overall, the model reproduces a seasonal cycle in PWS and northern Gulf of Alaska, and the results provide a good agreement between model and WOD data and remote sensing data.

More recently ROMS-CoSINE model simulations have been run to produce forecasts for the PWS 2009 field experiment. During the first week of the field experiment, the weather was quite stormy with abundant rainfall, and no useful remote sensed ocean color images were available. On August 2, the weather was clear and there was a good MODIS image showing surface chlorophyll distribution. We compared the modeled monthly (July) averaged chlorophyll with the MODIS derived chlorophyll, (Figure 45). Due to the cloud coverage, which reduces the surface light level, for the weeks before August 2, we do not know how phytoplankton growth evolved, i.e. there is little information about temporal variation of chlorophyll. However, in general, the model was able to reproduce a similar level of chlorophyll values for the PWS comparing to the MODIS observations. Also, the modeled sea surface temperature (SST) compares very well with the Advanced Very High Resolution Radiometer (AVHRR) derived SST. In part, this is due to the fact that the ROMS assimilates the observed information, including both in situ and remote sensing products, which constrains the physical processes in the ROMS. Due to lack of biological observations, we could not assimilate biological information into the model. A post hoc comparison is however ongoing.

As well as comparing the modeled results with the remote sensing observations, we also compared the ROMS-CoSINE predictions with limited in situ observations. There were three moorings in the PWS during the field experiment which collected continuous records of temperature and chlorophyll. Due to technical and communication issues, the mooring data were not included into the data stream until near the end of PWS field experiment, so we couldn’t conduct near real time model-data comparison. However post hoc comparisons were conducted between the modeled surface chlorophyll and SST and the mooring observations at Esther Island (Figure 46), Naked Island (Figure 47), and Port San Juan (Figure 48). Overall, the ROMS reproduced the observed temperature quite well. For the chlorophyll comparisons, the ROMS-CoSINE was able to reproduce a similar order of chlorophyll level at all three locations, but the model could not reproduce the large temporal variation of chlorophyll at Naked Island and Port San Juan, especially during April and May.

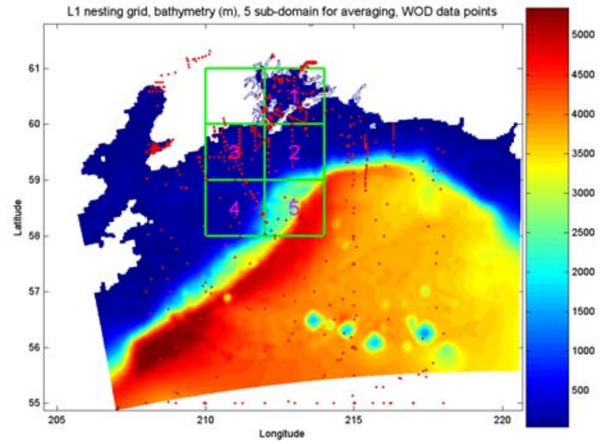


Fig. 44. WOD data points in PWS and Gulf of Alaska, and 5 domains for domain averaged physical and biology parameters. PWS is Domain 1 and the Seward Line inner domain is domain 3.

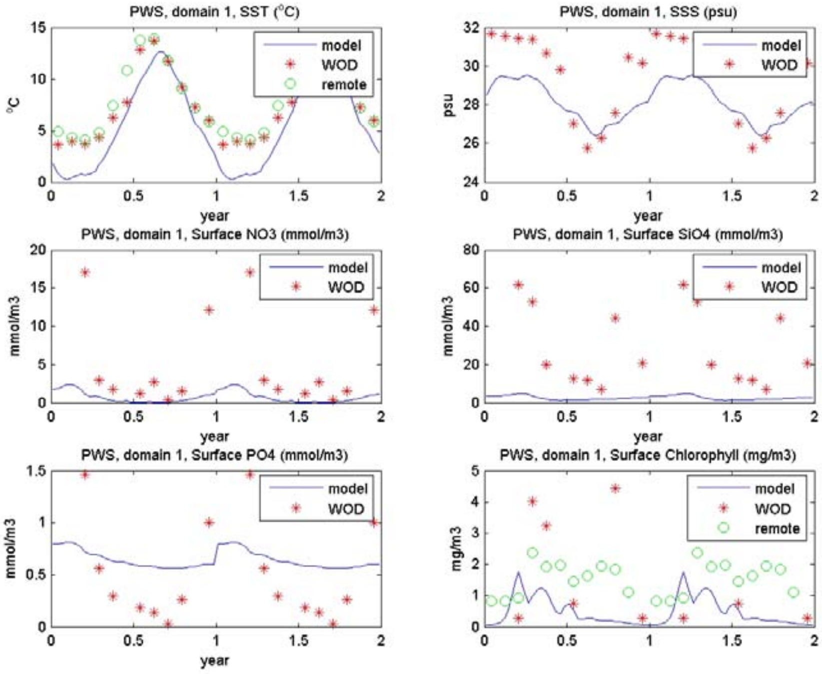


Fig. 45. Comparison between model output, WOD 2009 data, and remote sensing data at PWS, domain 1.

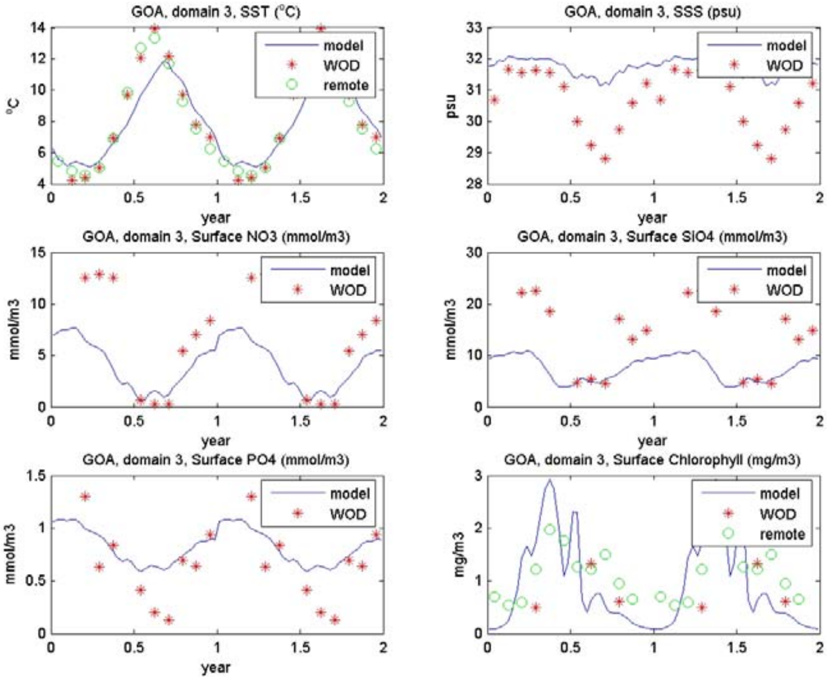


Fig. 46. Comparison between model output, WOD 2009 data, and remote sensing data at Seward Line inner domain, domain 3.

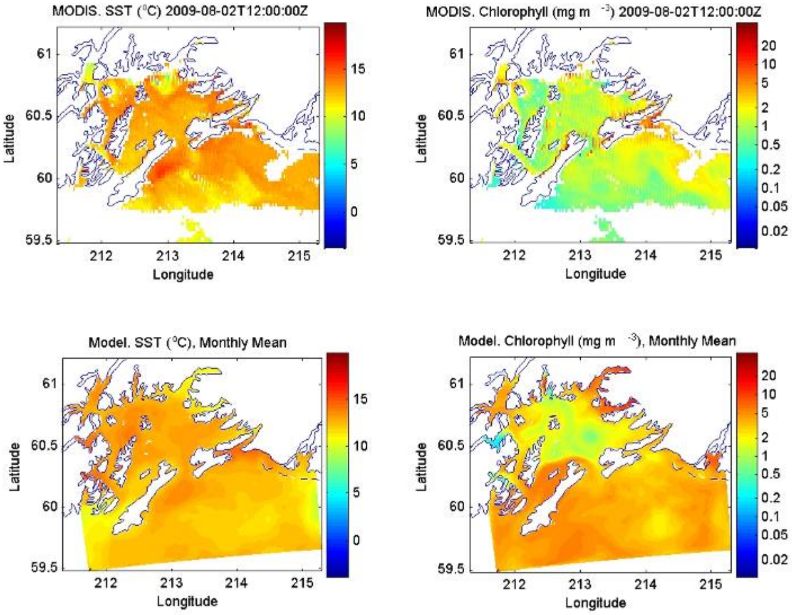


Fig. 47. Comparison between the modeled (lower panel) and the satellite observed sea surface temperature (SST) and chlorophyll.

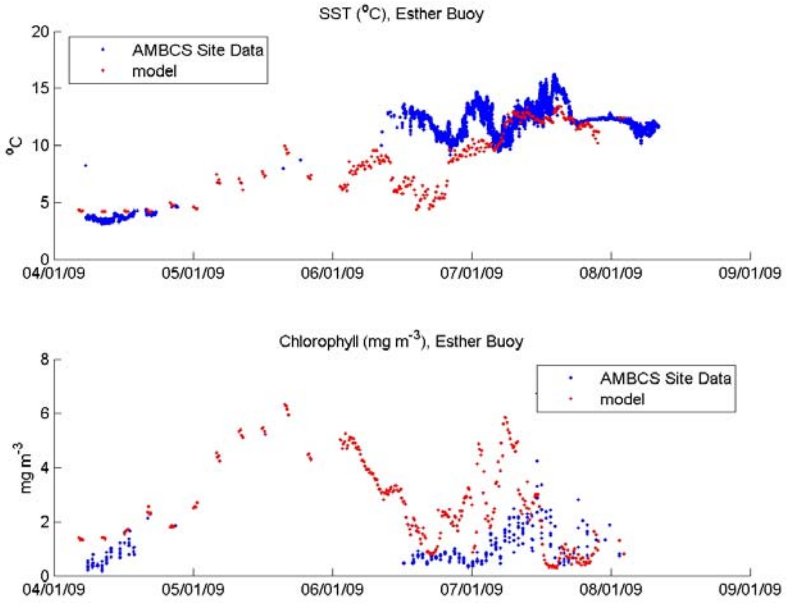


Fig. 48. Comparison of measured and modeled SST and chlorophyll at Esther Island. For observed chlorophyll, only those data measured around mid-night are used. The frequency of model output is once every five days in April-May and 4 times a day in June.

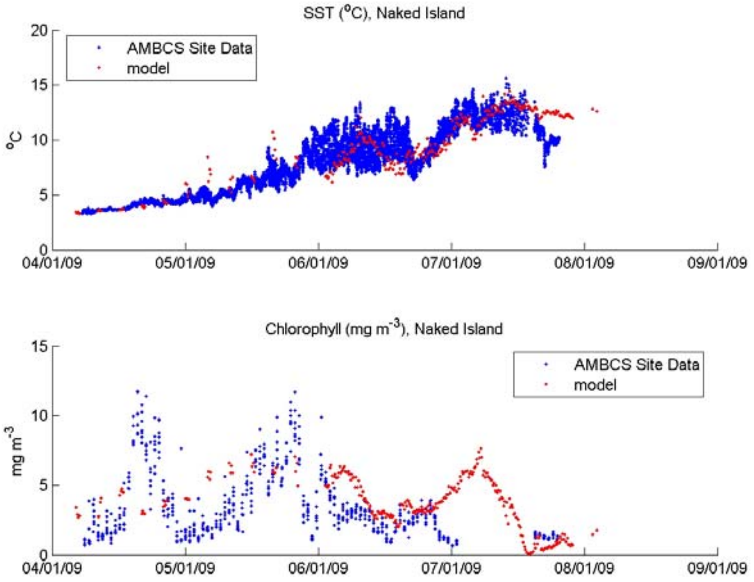


Fig. 49. Comparison of SST and chlorophyll between in situ data and model output at Naked Island.

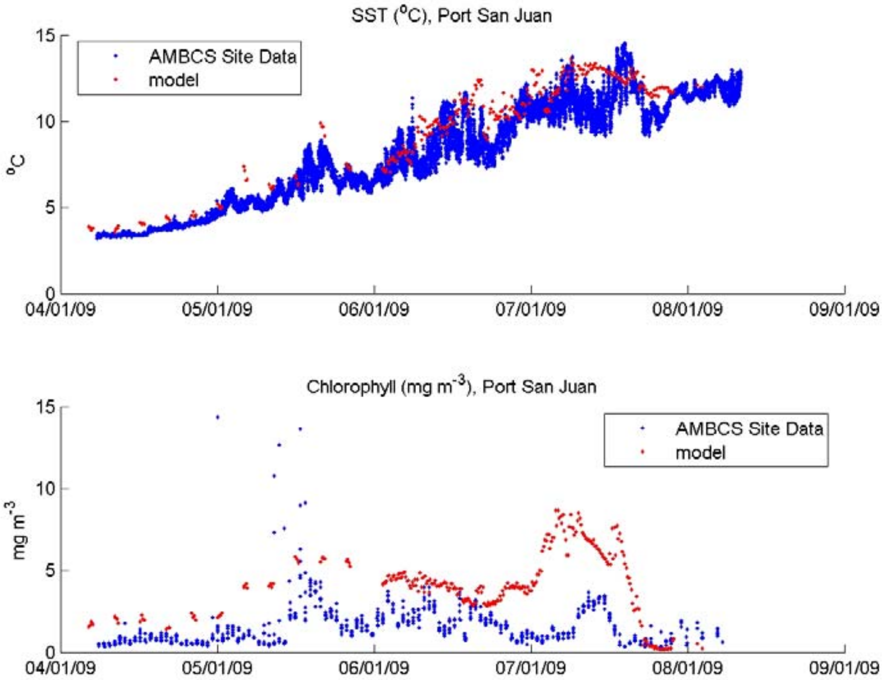


Fig. 50. Comparison of SST and chlorophyll between in situ data and model output at Port San Juan.

<u>GNOME forecasts</u>

NOAA Hazmat's participation in the Sound Prediction 2009 Field Experiment helped develop a better mutual understanding of modeling real-time and predictive circulation which would be useful in the event of an actual oil spill. Local representation was provided by the Alaskan Scientific Support Coordinator and support was also provided by the NOAA Seattle office with the GNOME oil spill trajectory model. The primary goal was to generate a trajectory forecast for the drifters using surface currents input from the JPL ROMS model and winds from AEFF WRF forecasts. The GNOME modeling group utilized the AOOS data management system to obtain ROMS and WRF forecasts in GNOME compatible formats. In addition, the HF Radar data was obtained from the National HF Radar server at Scripps. The 3 most important observations for an oil spill response are 1) the extent of the spill (i.e., dispersion) based on direct overflight observations, 2) wind observations and forecasts, and 3) surface currents from HF radar and forecast models such as ROMS.

Alyeska Tactical Oil Spill Model (ATOM) forecasts

Since 1991, Alyeska has run the ATOM model developed by Applied Science Associates (ASA). ATOM is a 2D and 3D trajectory and fates model that integrates spatial current data in a variety of formats and surface winds. The Alyeska stakeholders typically use tidal hydrodynamics, point observations, and forecasted winds. However, ASA has been working on future developments that allow ATOM to integrate a wider variety of metocean data that is available in NetCDF format (CF Compliant). Alyeska and ASA operated the model during the experiment to compare trajectories with the deployed drifter paths. ASA worked with the data providers from the field experiment to evaluate integration of real-time data into the model - primarily model output and not data from an ocean forecast model (ROMS) and meteorology model (PWS-WRF), as well as integration of drifter trajectories. ASA ran a matrix of trajectories using different forecasts including:

- Regional ROMS
- Regional PWS-WRF
- U.S Navy NCOM
- HF Radar Observations
- NWS National Digital Forecast Database (NDFD) Winds
- Global Forecast System (GFS) Winds

The primary purpose of the modeling exercise with ATOM was to evaluate the data integration challenges and not to quantitatively evaluate the skill of the model products against the drifter tracks. However, as part of the data management exercise, a number of trajectories were run (Figure 49) to do some comparisons of model trajectories to specific drifter tracks.

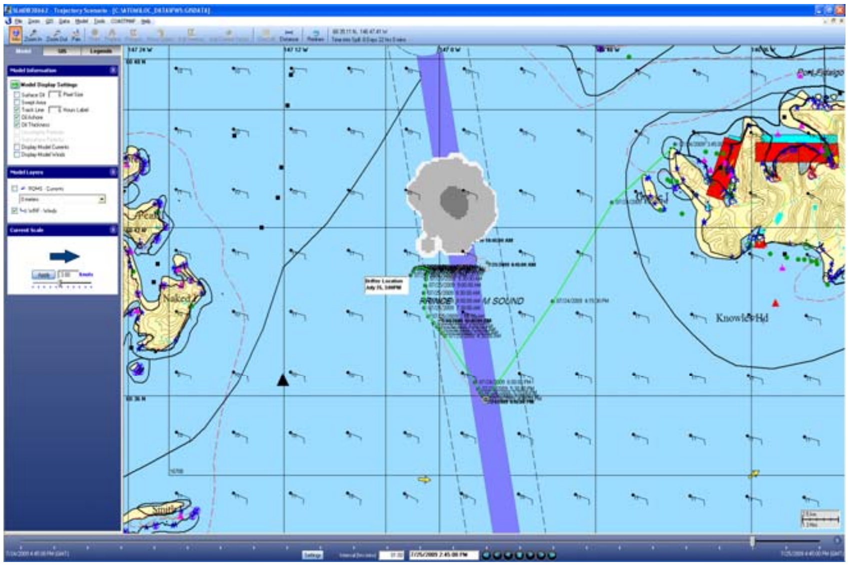


Fig. 51. ATOM comparison of oil spill trajectory forecast at 3:00 pm (Grey regions) July 25 with drifter location (white label). Oil Spill Forecast created with ROMS currents.

Also as part of the data management activity, ASA built code to generate and publish Keyhole Markup Language (KML) data for consumption by Google Earth. This data included drifter tracks, Lagrangian predictions, and the metocean data. KML files were created that included time-varying data and evaluated use of Superoverlays within the KML to handle gridded data. The data was published on the Amazon Cloud (Figure 50).

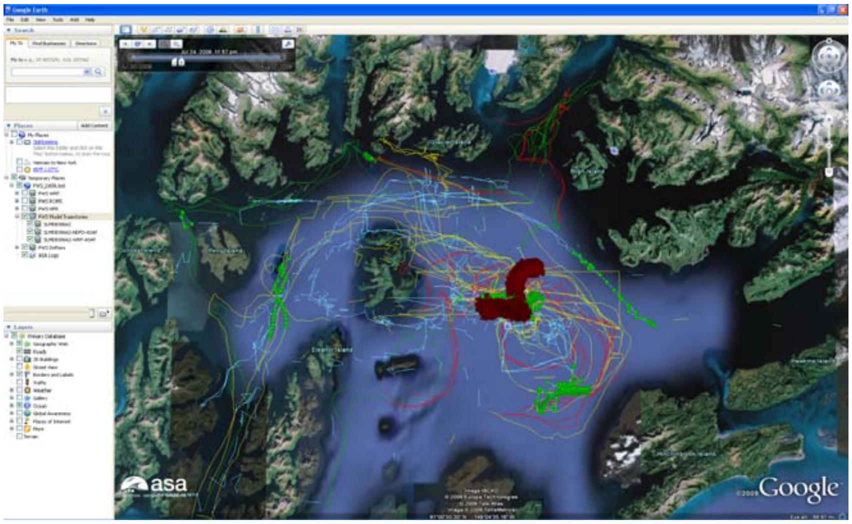


Fig. 52. Data from the Sound Prediction 2009 field experiment published on the Amazon Cloud.

Search and Rescue Optimal Planning System (SAROPS) forecasts

ASA is working also with the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), and the United States Coast Guard to integrate next generation ocean and meteorological forecasts, enhanced through the use of satellite data, with the U.S. Coast Guard's search and rescue (SAR) planning tool: SAROPS.

SAROPS became operational in 2007 and is the system used by all of the U.S Coast Guard SAR Planners. SAROPS uses a sophisticated animated grid model to project how/where floating persons or objects might move. It allows searchers to define the situation, access environmental data such as wind and water current patterns, compute drift trajectories, simulate environmental hazards, and develop a comprehensive search plan with available resources. The two most important input environmental parameters for SAROPS are:

- Atmospheric surface (10-meter) wind velocity
- Ocean surface current velocity

Currently, SAROPS accesses these data sets through the Environmental Data Server (EDS), which manages a number of global and regional wind and current data sets from both observations and computer forecast models. This project will improve the input for SAROPS by fully integrating NASA remote sensing measurements using data assimilation to create improved model forecasting products which will allow the U.S Coast Guard to improve the quality of their predicted search areas. As ASA had an operational Lagrangian model for Alaska with ATOM, it was used as a proxy for SAROPS. Specific recommendations stemming from the PWS field experiment include:

1. Work with modelers to make sure that data and model output have NetCDF compliant time stamps (e.g. fix days since 0000-00-00)
2. Check the coordinates – 0-360 / -180 - 180.
3. Add support for curvilinear method for wind forcing
4. Add EDS support for Arakawa grid staggering - Types A(existing),B(existing),C(Needed!),D(Less common)

5. Improve integration of drifter data. Would really like to see a National Server that aggregates SLDMB and other drifter data with uniform access. Will explore use of standard NetCDF data for drifters.
6. In general, it would be good to see all HF Radar data go to NOAA National Server so EDS can access data from that server.
7. The goal is that the ROMS and PWS-WRF operational model data will be available on the EDS for testing with SAROPS by the end of June 2010.

Outreach and Education

AOOS and COSEE (Center for Ocean Sciences Education Excellence) Alaska combined resources to use the PWS FE as a major opportunity for outreach and education to Alaskans and the nation. This collaboration also involved the Alaska Sea Grant Program, the Prince William Sound Science Center and the UAF School of Fisheries. The field experiment was utilized as a tool for outreach about AOOS, ocean observing and forecasting, oceanographic technologies, and the value of ocean ecosystems. This was accomplished through the use of podcasts, blogs, publications, the AOOS website, and a series of public events in Anchorage, Cordova, and Valdez.

Conclusions

The 5 year AOOS demonstration of an ocean observing system in PWS was a success in terms of collecting field observations and generating model forecasts of weather, wave and ocean conditions and providing these in near real-time through the internet. The project was qualitatively successful in also demonstrating the direct and indirect benefits of an ocean observing system for the commercial and recreational boating communities, oil spill response, and search and rescue operations. The utility of the ocean observing system for fishery management will be addressed in the near future as information products are developed and made more accessible from the web site.

Many of the observational components and forecast models performed well and important lessons were learned from these as well as the components that underperformed. The following is a brief summary of each component and what was learned from these observational and modeling efforts.

The modeling groups recognized early in the process that a standardized bathymetry was needed. There were several bathymetric datasets available but none were of adequate resolution for the wave model. AOOS worked closely with the ADF&G group in Homer to produce a high resolution map useful for identifying fish habitats and was also adequate for resolving fine scale features that affect wave height in the nearshore shallow waters of PWS. This dataset was derived from the most recent NOAA mulitbeam surveys in PWS combined with older data where multibeam surveys had not been completed. The dataset was made available in 2006 on the AOOS web site and became the standard for the 5 year project.

The AMBCS SnoTel weather stations deployed at sea level were a major improvement over the Very High Frequency (VHF) radio systems they replaced. The new stations are part of a national NRCS program providing weather and snow depth measurements in real time. These stations performed reliably and within budget for the entire 5 year demonstration. The only exception was a station deployed at the Nuchek Spirit Camp or which there were frequent data gaps due to poor telecommunications. Several of the stations were deployed at fish hatcheries and utilized on-site power. These stations were capable of transmitting data through a satellite internet connection and included live web cam images. These images and real time weather data are an example of an AOOS product that is highly desirable to various user groups.

SnoTel stations were planned for 5 sites at elevation and only 2 were actually deployed. The Mt. Eyak station was installed in 2004 and the Valdez Salomon Gulch station in 2006. After a four year process, permits were finally secured from the U.S. Forest Service to deploy 3 new SnoTel stations on Chugach National Forest lands around Prince William Sound. However, with only one year remaining for the five-year demonstration and with uncertain long term funding from either AOOS or OSRI, a short term deployment was considered inappropriate. Following discussions among the PWS investigators the decision was made to postpone deployment until long term maintenance funds can be secured for the new stations.

The NDBC buoy upgrades were completed in 2008 when a new buoy (46107) was deployed in Montague Strait to measure wave heights and period. The location of this buoy was coordinated with the PWSOS mooring program. The Hinchinbrook Entrance buoy 46061 was moved in 2006 to a location aligned with the PWSOS moorings. This buoy was upgraded with a downward looking ADCP and CT however cabling issues resulted in no data being reported from this buoy. The upgrades to the central Sound buoy 46060 and the NW PWS buoy 46081 were completed in 2004 but these are not reporting due to technical issues. The long and frequent data gaps from the buoy records are a function of the 2-year maintenance cycle and the difficulty in obtaining the required logistical support from US Coast Guard Buoy Tenders when malfunctions occur.

The deep water mooring planned for the central sound was never deployed. This mooring was intended to help determine the magnitude and frequency of water renewal in deep basins of PWS. Data was to be used to help validate and improve circulation forecasts from the ocean circulation models which require information on residence times of water masses. The mooring hardware was purchased with AOOS funds, an acoustic release was borrowed from the University of Alaska Fairbanks, and a CTD was purchased with funds provided by the Oil Spill Recovery Institute. However the project never received the required state permits and the deployment has been postponed indefinitely.

The nearshore moorings planned for deployment around the perimeter of the sound were deployed on existing moorings operated by Alyeska Pipeline at Port San Juan, Esther Island, and Naked Island. The Port San Juan and Esther installations communicated through the internet but the Naked Island site did not. The mooring in Port San Juan had been transmitting data since October 2007, the Esther Island mooring since 2008, and the Naked Island mooring since 2009. The initial CT recorder deployed near Port San Juan experienced severe galvanic corrosion, and was replaced in May 2008; the mooring cage was reconfigured at that time to prevent further corrosion. A cleaning visit was made to the mooring on September 5th 2008 and the instruments were in satisfactory condition. Arrangements were made to have future cleaning visits done by a local firm (McLaughlin Environmental Services). While electrolysis was not anticipated to be a problem, in March 2010 Alyeska requested that all the instruments be promptly removed because electrolysis had damaged the mooring hardware. A new mooring is still planned for the Tatilek location in 2010 however the corrosion issue should be addressed prior to this deployment.

The thermosalinograph boat surveys provided supplemental hydrographic data since the spring of 2006. The *F/V Alena K* is instrumented with a thermosalinograph to acquire underway measurements of near-surface temperature and salinity, a fluorometer to measure chlorophyll, and a transmissometer to quantify turbidity. From early spring 2006 to January 2008, the *F/V Alena K* also conducted CTD casts at seventeen locations during each survey with the goal of estimating the seasonal cycle of fresh water content in the sound. The thermosalinograph cruises have now been discontinued due to lack of funding.

Discharge measurements from the Copper River stream gauge have been communicating in real-time since spring 2006 and were assimilated into the nested ROMS ocean circulation model to improve the forecasts of ocean circulation. The data acquired form this stream gauge was invaluable to the performance of the ocean circulation model. An MOU has been drafted and signed between the PWS Science Center and the U.S. Geological Survey to continue the operation of this gauge.

The High Frequency (HF) Radar instrumentation in PWS at Shelter Bay and at Knowles Head were intended to provide real-time surface currents of the central basin.

HF radar provided critical, high quality data to the field experiment. Twice during the two-week period, the system failed due to technical problems, but was restored by the HF radar team. Due to the remote setting in the Sound, installing the system off the power grid and away from phone/internet communication presented a unique challenge. The sites could only be accessed by boat during relatively calm weather (which didn't often occur during the field experiment time). While implementing HF radar is logistically difficult and costly, all PI's agreed it was a crucial part of the project. The age of the system that was used caused particular problems that would likely not occur if a newer system was used. Validating data from 1 of the 2 radars would be useful in the future if 1 of the radars goes down, but the other continues to perform.

The intent of the biophysical monitoring component of the project was to collect data that could be used to link primary and secondary biological productivity to ocean conditions. Budgets in 2005-2007 had funds to deploy fluorometers on the deep water moorings as well as ISUS Nitrate sensors. To measure abundances of zooplankton relative to water volume transport and physical properties of flow through the major entrances of PWS the 2005 budget included funds for a Tracor multifrequency (256kHz - 3.0mHz) acoustic plankton sampler (TAPS) for the Hinchinbrook and Montague mooring arrays. The fluorometers were purchased and deployed but funds for the nitrate sensor and the TAPS were reallocated and these datasets were never realized.

The Sound Predictions 2009 field experiment utilized some of the most sophisticated technology available and the expertise of a team of scientists from across Alaska and the nation. The organizational and logistical obstacles encountered were formidable due mostly to the remoteness of the study area and the distributed nature of the resources and assets focused on PWS for the two week period. Planning for the experiment took over two years and monthly telephone conferences for all the participants began six months before the experiment and continued twice daily during the experiment. Preliminary results from the field experiment include:

1. Wind direction was very hard to predict in light and variable conditions (< 5 m/s) and terrain problems persist in some areas of PWS.
2. SWAN wave height forecasts (in general) are over-predicted with the largest errors for smallest waves (< 0.5 m).

3. With data assimilation the ROMS model correctly predicted drifter trajectories and vertical structure of the water column.
4. Quantifying fresh water input from local and regional watersheds is difficult but ultimately essential to resolve the buoyancy forcing.
5. HF radar surface current mappers are an essential assimilation component of this observing system.
6. There are limitations to HF radar data relative to drifter trajectories and a better understanding of HF radar performance during different phases of the tide may be needed.
7. NPZ model performance is likely to improve with better local observations of light attenuation in turbid (glacial) water.

Program Review Summary

TBD

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