Twenty-Five Years After the *Exxon Valdez* Oil Spill:

NOAA's Scientific Support, Monitoring, and Research

DEPARTMENT OF COMMERCE • National Oceanic and Atmospheric Administration (NOAA)
National Ocean Service • Office of Response and Restoration • Emergency Response Division

NOAA's Office of Response and Restoration

NOAA's Office of Response and Restoration (OR&R) is a center of expertise in preparing for, evaluating, and responding to threats to coastal environments, including oil and chemical spills, releases from hazardous waste sites, and marine debris.

To fulfill its mission of protecting and restoring NOAA trust resources, the Office of Response and Restoration:

- Provides scientific and technical support to prepare for and respond to oil and chemical releases.
- Determines damage to natural resources from these releases.
- Protects and restores marine and coastal ecosystems, including coral reefs.
- Works with communities to address critical local and regional coastal challenges.

OR&R is comprised of three divisions: Emergency Response, Assessment and Restoration, and Marine Debris. Collectively, the Office of Response and Restoration provides comprehensive solutions to environmental hazards caused by oil, chemicals, and marine debris.

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Preface

During the spring and summer of 2010, the eyes of the nation were riveted on the Gulf of Mexico. In April, the mobile offshore drilling unit *Deepwater Horizon* exploded and sank, with a tragic loss of 11 lives. For three months, oil and gas spewed from the uncontrolled wellhead a mile below the surface of the water. Remote images of the nightmarish release were transmitted from the abyss and could be viewed around the clock and around the world. On the surface and on the shorelines of the adjacent Gulf coast states, the implications were painfully and frustratingly obvious: vast amounts of oil that exceeded recovery and containment capacity; heavily coated wildlife icons like pelicans and sea turtles; and soiled white sand beaches that ordinarily would be crowded with swimmers and sunbathers.

It would be America's largest oil spill.

Deepwater Horizon on April 21, 2010. U.S. Coast Guard photo.

But two decades earlier, there had been another oil spill. It was large; it involved one of the world's largest oil companies; it fouled and killed iconic wildlife species; it was contentious and adversarial; it changed the way we do business.

It was the *Exxon Valdez* oil spill, and it assumed and retained the title of "nation's largest spill" until the *Deepwater Horizon* supplanted it in 2010. 2014 marks the 25th anniversary of the *Exxon Valdez*. This is the story of the incident and NOAA's involvement in the response, operational monitoring, and research.

Table of Contents

The Accident

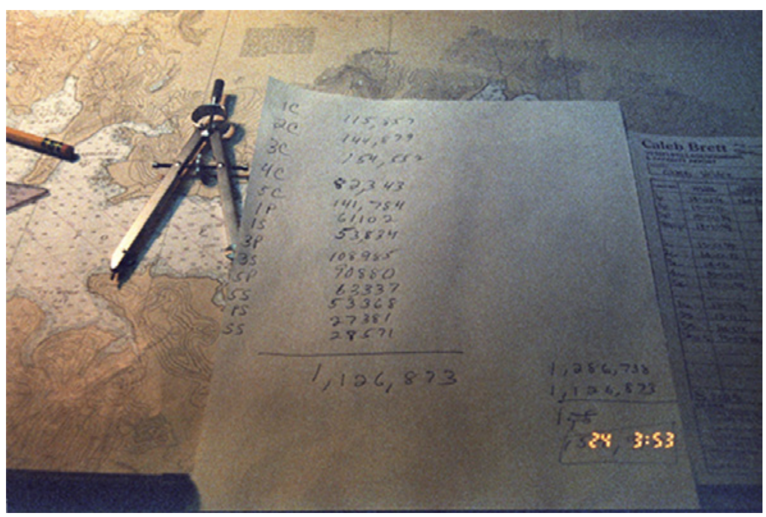
The *Exxon Valdez* departed the Alyeska Pipeline Terminal in Valdez, Alaska on Thursday evening, March 23, 1989. Built in 1986, the 987-foot/300 m flagship tanker was loaded with just under 1.3 million barrels (roughly 54 million gallons) of North Slope crude oil and was bound for Long Beach, California.

Exxon Valdez at Outside Bay, May 1989. Photo by Gary Shigenaka, NOAA.

Just after midnight on March 24—Good Friday—the vessel went hard aground on Bligh Reef, at the southern end of Valdez Narrows.

Within a half hour of the impact, the chief mate determined that all center and starboard cargo tanks had been compromised and were discharging oil. Additionally, two starboard ballast tanks were also holed and taking on seawater. The extent of the damage caused immediate concerns about the short-term stability and structural integrity of the ship itself.

The photograph at right, taken by Alaska Department of Environmental Conservation District Office Supervisor Dan Lawn, indicated that by the time that he and U.S. Coast Guard investigators boarded the *Exxon Valdez* less than four hours after the grounding, nearly 7 million gallons had been released. The National Transportation Safety Board later estimated that by 6:00 a.m. on the morning of March 24, 215,000 barrels—9 million gallons—had been lost. Ultimately, the total amount of oil spilled was estimated to be 11 million gallons. It would be the largest oil spill into U.S. waters.



Estimating the oil lost from the *Exxon Valdez* at 3:53 a.m., March 24, 1989—accounting performed in the cargo control room of the stricken tanker. Calculations showed that of 1,286,738 barrels (bbl) total cargo, 1,126,873 bbl remained (indicating that 159,865 bbl had been lost). Photo by Dan Lawn.

In the days and months following the grounding, the *Exxon Valdez* gained notoriety because members of the tanker crew, including Captain Joseph Hazelwood, were known to have been drinking in several establishments in its namesake town of Valdez hours before the vessel departed. Although it has become part of the lore of the spill that Hazelwood was intoxicated at the time of the grounding, it should be noted that an Alaskan jury acquitted him of the formal charge of operating a vessel under the influence. The jury did find Hazelwood guilty of negligent discharge of oil, a misdemeanor. He was fined $50,000 and sentenced to 1,000 hours of community service in Alaska.

In its formal investigation, the National Transportation Safety Board determined that the probable root causes of the spill were more complex, and extended beyond the bridge of the *Exxon Valdez* itself:

1. The failure of the third mate to properly maneuver the vessel, possibly due to fatigue and excessive workload;

2. The failure of the master to provide a proper navigation watch, possibly due to impairment from alcohol;
3. The failure of Exxon Shipping Company to supervise the master and provide a rested and sufficient crew for the *Exxon Valdez;*
4. The failure of the U.S. Coast Guard to provide an effective vessel traffic system;
5. The lack of effective pilot and escort services.

The *Exxon Valdez* struck Bligh Reef with great force, rupturing eight of eleven cargo and two ballast water tanks, as well as the forepeak hold. It was temporarily immobilized and impaled on the reef, but it was dangerously unstable and—despite the loss of a large amount of North Slope crude—still loaded with most of its cargo. The imperative to remove the remainder of the oil from the ship was an obvious one, but was complicated tremendously by the change in buoyancy that would result from the transfer ("lightering") of the *Exxon Valdez* cargo to other tankers: there was the potential for the grievously injured tanker to shift or float free from the reef but out of control, possibly grounding again and compromising even more of its cargo tanks.

Photograph of one of the boulders lodged in the frame of the *Exxon Valdez*, as found in the drydock of National Steel and Shipbuilding Company, San Diego. From the collection of Gary Shigenaka, NOAA.

Exxon Valdez and *Exxon Baton Rouge* at Bligh Reef, preparing to lighter cargo. NOAA photograph.

Plans for lightering the remaining cargo began almost immediately. The inbound tanker *Exxon Baton Rouge* was diverted to be the receiving vessel for offloaded *Exxon Valdez* cargo oil, and by the evening of March 24 was alongside the crippled ship. While actual transfer began on the morning of March 25, it did not proceed in earnest until the U.S. Coast Guard Pacific Strike Team mobilized to assist in the process late that evening. The lightering continued over the next two days, but by March 27, the weather had deteriorated significantly. Winds gusted to over 70 knots and as the ship became increasingly more buoyant, concerns about stability and control grew. On April 1, the ship's crew was put on alert about the increased instability of the *Exxon Valdez*.

Meanwhile, on March 29, the *Exxon Baton Rouge* reached its capacity and departed. The *Exxon San Francisco* took its place until April 2, followed by the *Exxon Baytown*. By the time the *Exxon Baytown* completed its round of lightering on April 4, a total of 1.024 million barrels (43 million gallons) of crude oil had been removed from the *Exxon Valdez*. An estimated 16,445 barrels (691,690 gallons) remained aboard.

The *Exxon Valdez* refloated around 10:30 on April 5. It was obviously necessary to move the tanker to a sheltered location where it could be surveyed in detail, stabilized, and made ready for transit to a west coast shipyard for major repairs. Rather than return it to Valdez Harbor, the U.S. Coast Guard Federal On-Scene Coordinator determined that the ship should be taken to an area already known to be oiled. On the evening of April 5, it was moved to Outside Bay, on Naked Island, where it would remain until June 23. After inspections, stabilizing repairs, and cleaning, the *Exxon Valdez* departed Prince William Sound—for what would be the last time—en route to National Steel and Shipbuilding Company in San Diego.

Shoreline cleanup at Point Helen (Knight Island) in Prince William Sound, September 3, 1989. Photo by Erich Gundlach.

The Response

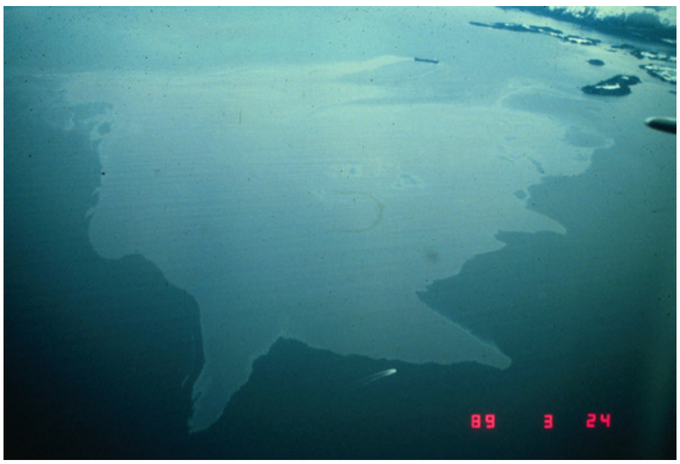
The initial response to the *Exxon Valdez*, in the early morning hours of March 24, was a nightmare of poor preparedness and execution that had been forewarned and foretold at least five years prior to 1989 by both the Alaska Department of Environmental Conservation and the U.S. EPA. The U.S. Coast Guard's official timeline of events documented the shortcomings once the ship's predicament became known:

> "Initial response efforts at the Port of Valdez under Alyeska's control are hampered by equipment casualties and holiday personnel shortages. As response personnel arrive at the Alyeska Terminal, however, Alyeska is unable to comply with the response timeliness provision in its own contingency plan that calls for initial response at the vessel within five hours of first notification.
>
> "Alyeska's only containment barge is tied up at Valdez Terminal, stripped for repairs. Barge was not certified by the CG to receive oil, but it could carry recovery bladders. Alaska's state contingency plan requires Alyeska to notify the state when response equipment is taken out of service. Satisfied the barge was seaworthy without repairs, Alyeska had not done so.

> "Before barge could be used, pollution gear had to be loaded. Crane riggers called at 0330. By this time, (Coast Guard) estimates 5.8 million gallons already discharged from the tanks."

As the pilot vessel ferrying them to the tanker in the first hours after the grounding made its approach, Coast Guard personnel reported encountering oil on the water some two hundred yards from the *Exxon Valdez*. They noted six to ten inches of oil adjacent to the ship, and "oil billows" along half its starboard length.

At first light on March 24, the gravity and scale of the situation became more apparent with helicopter observations that the slick was already 1,000 feet wide and four miles in length. A later Coast Guard overflight confirmed the nighttime observations from the water of "extremely heavy" oil within 20-30 feet of the ship.



The relatively contiguous and intact oil slick from the *Exxon Valdez* (upper center right) on the first day of the spill, March 24 1989. Photo by Alan A. Allen.

It was more than apparent that this was a major release that would require an equivalent response. The *Exxon Valdez* oil spill presented many challenges related to geographic remoteness, rugged shorelines, severe weather, robust but sensitive biological habitat, and commercial and subsistence fisheries resources—among others. The response would reflect this in its size, complexity, and frequently confrontational relationships inside and outside the response.

Given the amount of oil already on the water and the potential for an even more catastrophic release, relatively novel options such as the use of chemical dispersants and in-situ burning (intentional combustion of oil on the water) were discussed as possibilities by the Federal On-Scene Coordinator and the Alaska Regional Response Team on the first day of the spill, and a first test application of the dispersant Corexit 9527[1] occurred the evening of March 24. However, interagency discussions and further operational preparations continued over the next few days. Between March 24 and March 28, six applications of dispersant were made, with mostly inconclusive or unsatisfactory results. Only three more application sorties occurred in April, and when the final extensively monitored test on April 13 showed no significant benefits, further use was discontinued. Although only eight actual applications took place, a total of around 45,000 gallons (170,000 liters) of dispersant had been sprayed.

In-situ burning yielded more promising results than did the dispersant applications. After assembling the specialized equipment needed for intentionally burning oil on the water from Cook Inlet and from Oregon, a test was conducted on the evening of March 25. Around fifteen thousand gallons (57,000 liters) of the spilled crude oil was collected and ignited, burning for around 75 minutes. The original volume of oil was reduced to a much smaller (around 10 m2) mat of burn residue. With these encouraging results, plans were made to apply the technique to the leading edge of the slick, and on the evening of March 26, Exxon received clearance to do so.

Unfortunately—the storm system that arrived in Prince William Sound on March 27 spread what had been a fairly contiguous surface slick far and wide, thereby eliminating a necessary prerequisite for use of in-situ burning (i.e., a relatively thick and contiguous oil layer) and—although another attempt was made on Tuesday, March 28, the oil had been mixed with water and no longer could be ignited. On Friday, March 31, Exxon declared that burning was no longer a viable response option.

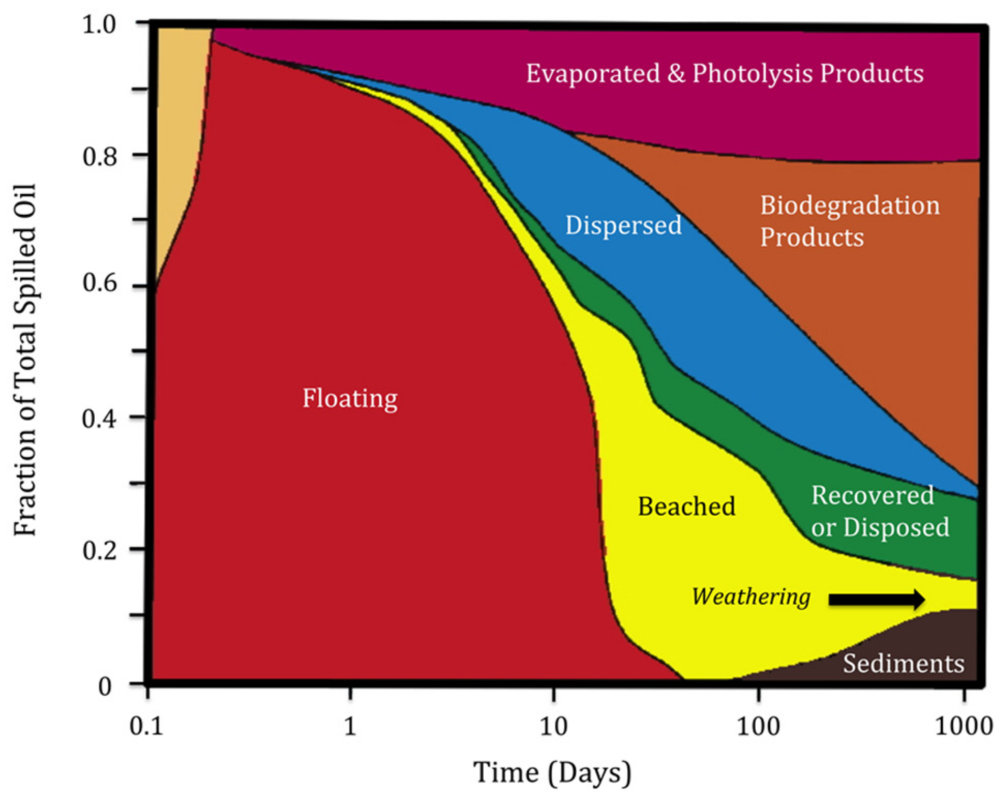
[1] Corexit 9527 would also be the first chemical dispersant applied to the *Deepwater Horizon* spill 21 years later.

The March 27-28 storm not only drastically restricted the effective use of most on-water response techniques, it also began pushing large amounts of oil ashore onto the beaches of Prince William Sound. NOAA spill scientists surveying initial impact areas on Smith and Little Smith Islands, and on Naked Island, reported variably heavy oiling with pools of emulsified oil, or "mousse," 10 cm in depth and up to 20 cm penetration in gravel beaches. Shoreline cleanup operations began on Knight Island on March 29.

Photograph of the *Exxon Valdez* in-situ burn test, March 25 1989. Photo by Alan A. Allen.

The oiling would eventually extend nearly 700 miles through Prince William Sound and down the Alaska Peninsula, and the largest spill cleanup operation in history would peak at an estimated 10,000 workers, 1,000 vessels, 100 aircraft and helicopters, and extend into four years. Exxon estimated its cleanup costs to be $2.1 billion.

Despite the unprecedented scale, duration, and cost of the response, modeling of the fate of the spilled oil by NOAA and other scientists estimated that the cleanup itself removed only a small portion (a little more than 10 percent) of the spilled oil from the environment. By far, the largest part of the total was naturally weathered or degraded.



Modeled fate of the spilled *Exxon Valdez* oil with time, showing relatively small proportion recovered by the cleanup (in green) after 1000 days. From Wolfe et al. (1994).

Shoreline cleanup operations in Northwest Bay, West Arm, June 1989. NOAA photograph.

The Toll

It is difficult to gauge and convey the impacts of an oil spill. Some effects are obvious: an oil-coated bird struggling on the shoreline, a sea turtle mired in thick floating oil in an offshore convergence zone. An easily understood measure of biological impact is the number of dead animals associated with a spill, and there is no disputing that the *Exxon Valdez* oil spill had profound lethal effects on a number of living resources in the spill area. But even this metric is not as straightforward as one might hope, as noted by the following frequently asked question from the *Exxon Valdez* Oil Spill Trustee Council:

Photo by Dan Lawn.

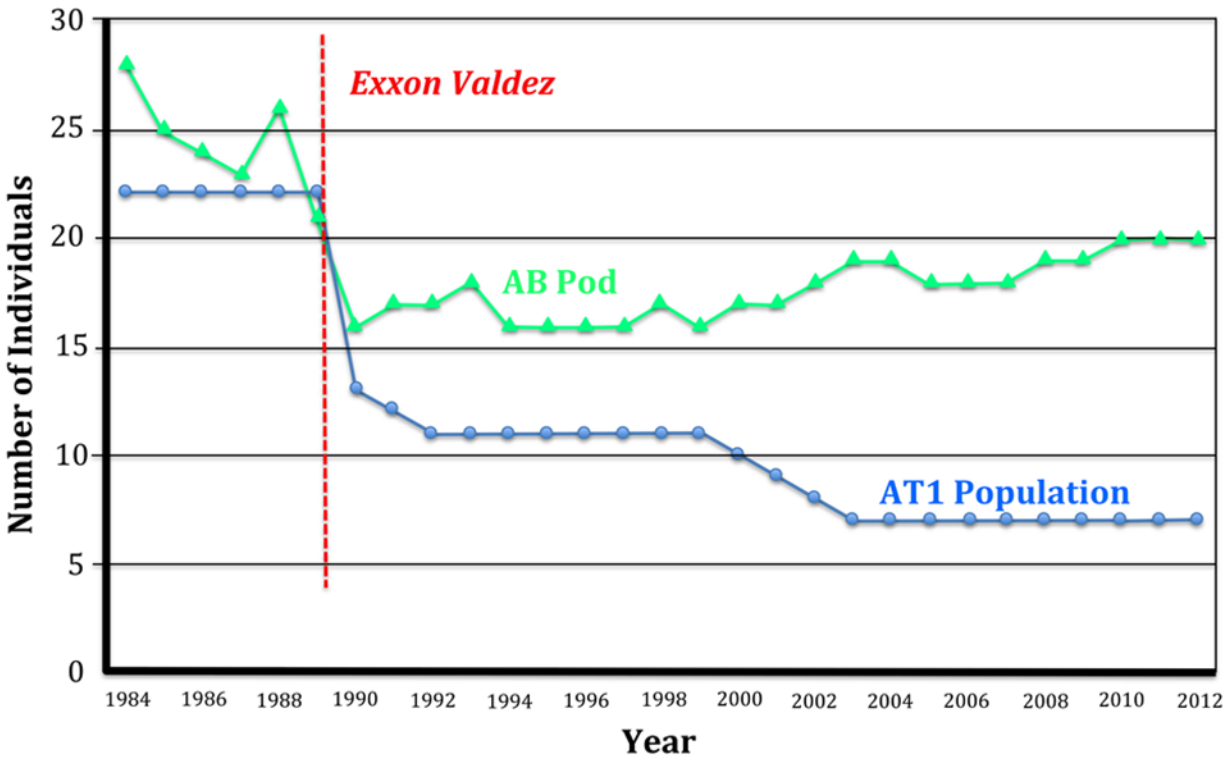
> "How many animals died outright from the oil spill?
>
> No one knows. The carcasses of more than 35,000 birds and 1,000 sea otters were found after the spill, but since most carcasses sink, this is considered to be a small fraction of the actual death toll. The best estimates are: 250,000 seabirds, 2,800 sea otters, 300 harbor seals, 250 bald eagles, up to 22 killer whales, and billions of salmon and herring eggs."

Direct mortalities were only the most evident of the *Exxon Valdez* oil spill's impacts. Long-term surveys of one of Prince William Sound's iconic species, the killer whale, reveal circumstantial but compelling evidence for profound effects that may lead to extinction in one orca subpopulation. The surveys also showed the great value of one of the rarest of all oil spill commodities: pre-spill data.

Prior to the *Exxon Valdez* spill, many marine mammal experts believed that cetaceans would avoid oil spills and thus minimize their exposure to toxic effects. However, in 1989 it quickly became obvious that for killer whales, this was not the case: orcas were photographed in oil, next to the tanker itself, and adjacent to oil skimming operations.

Skimming operations for *Exxon Valdez* with orcas in close proximity. Photo by Dan Lawn.

The effects of this exposure would not become apparent for many years, and they became apparent only because whale researcher Craig Matkin of the North Gulf Oceanic Society has been studying the killer whales of Prince William Sound since 1984, five years before the spill. The population trends in two major groups of orcas that frequent Prince William Sound (shown on next page) suggest simultaneous reductions in numbers of whales timed with the oil spill and cleanup. Continued monitoring since the spill has reflected patterns of slow recovery (for AB Pod) and no recovery (AT1 group). Matkin has described the prospect for the latter group to become extinct within the next several decades as "likely."



Twenty eight years of killer whale monitoring in Prince William Sound, showing synchronous decline of two populations coincidental with *Exxon Valdez*, slow recovery of AB Pod, and lack of recovery in AT1. Courtesy of Craig Matkin, North Gulf Oceanic Society.

In 2003, a synthesis of a number of spill studies published in *Science* magazine supported the idea that more subtle, indirect, and sublethal exposures to low concentrations of residual oil bore the potential for profound long-term adverse effects on the Prince William Sound ecosystem. The results from monitoring of killer whales are consistent with this. However, Exxon-supported researchers have disputed the extent and longevity of impact, in court and in the literature.

There is still residual oil along the shorelines of Prince William Sound. It is not a large volume, relative to the amount spilled. But pockets of it are surprisingly unweathered, given the passage of a quarter century.

Lingering oil on Eleanor Island, August 2013. Photo by David Janka, *Auklet* Charter Services.

Lingering oil at Herring Bay, Knight Island, February 18, 2014. Photo by David Janka, *Auklet* Charter Services.

The latest federal and state assessments of recovery from the *Exxon Valdez* spill indicate that, as expected, measurable impacts have diminished over the last two decades. In 2013, even two vertebrate species that had shown consistent and lengthy signs of exposure and effects—harlequin ducks and sea otters—appeared to have recovered.

A handful of resources and uses are considered to remain impaired and unrecovered, with one of the larger question marks represented by the status of Pacific herring. Few species of fish are of greater ecological importance than the herring, a species central to the diet of many birds, fish, and marine mammals in Alaska. It was also the basis of an important commercial roe fishery. The Prince William Sound herring population collapsed 4 years after the *Exxon Valdez* oil spill, resulting in speculation by many that the spill had been the cause of the crash, a notion that received new life and wide circulation during the *Deepwater Horizon* spill.

Herring spawn in Prince William Sound, 1989. NOAA photograph.

Researchers at the NOAA/National Marine Fisheries Laboratory in Auke Bay, AK convened a series of workshops to reexamine the role of oil in limiting the recovery of herring in Prince William Sound. The group concluded that while there were immediate toxicity effects of the spill to herring embryos and larvae in 1989, the present-day lingering oil residues were not believed to have a continuing impact. Nevertheless: just as the current and continued lack of recovery of herring could not be conclusively linked directly to the oil spill, the spill also could not be eliminated as a root cause. There are other factors to consider as well. Disease continues to afflict the Prince William Sound population, while others in Alaska do not show this type of continuing stress. In addition, predation pressure from a growing population of humpback whales may also play an increasing role in limiting herring abundances. For now—the spill impacts and recovery status for this species remain uncertain.

Pacific herring, *Clupea pallasii*. Photo by Mandy Lindeberg, NOAA Fisheries, Auke Bay Laboratory.

Is Prince William Sound recovered from the *Exxon Valdez* oil spill, a quarter century later? At one level, the answer is simple—and it is "no." This is in spite of a steady progression of originally injured resources and services that have moved from the "not recovered" column to "recovered" in the last 25 years. For many, the question of regional recovery is an "all or nothing" proposition: until it is all recovered, Prince William Sound is not recovered. There is oil in the beaches; a population of orcas teeters on the brink; an important fishery remains impaired and a question mark.

Prince William Sound is, therefore, not recovered.

However … it is difficult to not recognize that a place of great natural beauty and importance that was despoiled in such a terrible and seemingly irreparable fashion is now—again—a place of great natural beauty and importance. It is both relevant and ironic to recall that Prince William Sound was also one of the most devastated regions during one of the state's other major disasters: the 1964 Great Alaskan Earthquake (the "ironic" descriptor stems from the fact that it occurred almost exactly 25 years to the day, on Good Friday, before the *Exxon Valdez* spill). In 1964, Prince William Sound endured some of the most severe impacts, with a human toll of 31 in Valdez and 23 in the village of Chenega from the earthquake and the resultant tsunami. The coastal shorelines of the Sound were substantially and irrevocably changed by uplift, and it is almost certain that recovery from that event was not yet complete when the *Exxon Valdez* grounded on Bligh Reef.

It may be that recovery from the *Exxon Valdez* spill and the Great Alaskan Earthquake will never be complete. However, it also appears that natural systems are resilient, to an extent that is surprising to us when we witness the initial effects of major disturbance. That is, without minimizing or downplaying real and documented impacts: nature accommodates insults imposed on it, and incorporates them into a new "normal."

Is this an excuse for complacency or an apology for those who would downplay environmental impacts? No. In the case of the *Exxon Valdez*, it is difficult to overstate or trivialize the deaths of hundreds of thousands of seabirds, the potential extinction of a group of cetaceans, or dismiss loss of a lifestyle for many human residents. In Alaska, there are increasing indications that human-caused changes are exceeding the capacity of some organisms and some habitats to accommodate those changes. As trustees for these resources, NOAA and other federal and state agencies will continue to seek understanding of the cumulative toll of many stressors in the natural system. This understanding is perhaps more important than ever, as we look toward an uncertain future of climatic change and increased use of other Alaskan regions like the Arctic.

NOAA's Role in Spill Response

The first U.S. National Contingency Plan was published in 1968 in response to a massive oil spill from the oil tanker *Torrey Canyon* off the coast of England the previous year. To both acknowledge and avoid the response problems faced by the British during this incident, U.S. officials developed a coordinated approach to cope with potential spills in U.S. waters. The 1968 plan provided the first comprehensive system of accident reporting and spill containment and cleanup. It also established a response headquarters in association with the U.S. Coast Guard, a national reaction team and regional reaction teams that were the precursors to the current National Response Team and Regional Response Teams.

NOAA command post, Valdez AK, June 1989. NOAA photograph.

The spill response role of NOAA had its beginnings on the continental shelf of Alaska in the mid-1970s. As oil development there grew imminent, the U.S. Department of Interior, as manager of the oil and gas leasing activities, initiated a multidisciplinary study program with NOAA to ensure that development and production did not conflict with statutory mandates to protect the marine and coastal environment. The interagency agreement created the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in 1975.

As part of its involvement with OCSEAP, in 1976, NOAA established the Spilled Oil Research (SOR) Team. The SOR Team was a network of coastal geologists, marine biologists, chemists, and oceanographers. Initially, this small group of scientists proposed intentionally spilling oil in Alaskan waters to provide information about oil behavior and to test physical models—but the notion of creating an oil spill, regardless of noble intent, was greeted with underwhelming enthusiasm and little support. As a result, the SOR Team shifted its focus to "spills of opportunity": when an accidental oil spill occurred, the SOR Team would mobilize quickly and go on-scene with the goal of gaining information to help minimize damages from future incidents.

Conveniently for the SOR Team, on December 15, 1976, the 640-foot Liberian-flagged tanker *Argo Merchant* ran aground near Nantucket Island—directly over Georges Bank, which, at that time, was one of the world's most productive commercial fishing areas. En route from Venezuela and bound for Salem, Massachusetts, the tanker carried 7.5 million gallons of residual fuel oil in one of its thickest, heaviest forms. Both government agencies and the scientific community recognized the seriousness of the situation. However, the Coast Guard, charged with directing the spill response and cleanup effort, was inundated with competing and often conflicting recommendations from all sides. Accordingly, the Coast Guard asked the NOAA SOR Team, with its cadre of technical specialists, to act as an informal liaison with the scientific community at the spill.

The final moments of the *Argo Merchant*, Nantucket Shoals, December 21, 1976. U.S. Coast Guard photo.

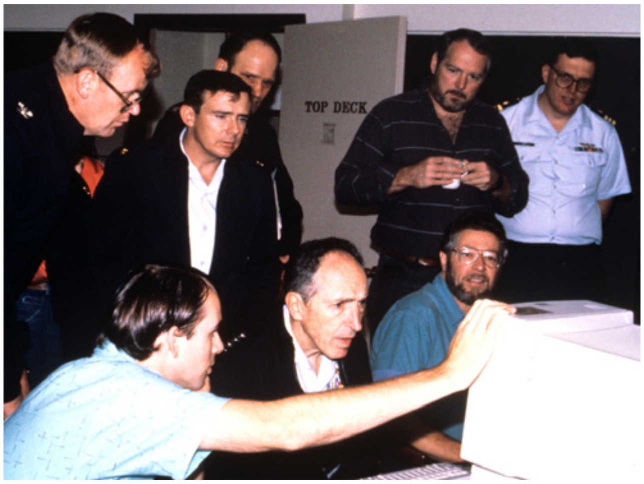
This informal relationship rapidly established its value; the Coast Guard began to rely on the SOR Team to address the complex scientific issues that arose at subsequent spills. The SOR Team, while continuing to investigate oil spill phenomena, acted as the Coast Guard's scientific advisor at spills that followed the *Argo Merchant*, including the *Amoco Cadiz*, off the Breton coast of France in 1978; and the IXTOC I well blowout in the Gulf of Mexico in 1979. By that time, the SOR Team had been renamed the Hazardous Materials Response Project, or HAZMAT.

Embroidered patch from the NOAA Spilled Oil Research Team, circa 1976. Photo by Doug Helton, NOAA.

In 1982, revisions to the National Oil and Hazardous Substances Pollution Contingency Plan formally codified NOAA's role as coordinator of scientific activities during spill emergencies. A new type of operational scientist was specified in the law to provide advice to the Coast Guard and other federal responders:

> "…during a response, the SSC (NOAA Scientific Support Coordinator)…is responsible for providing scientific support for operational decisions and for coordinating in-scene scientific activity."

NOAA/HAZMAT designated nine regionally-based SSCs to facilitate ready access to the science assets of NOAA by the Coast Guard and other federal and state agencies. Administrative and technical expertise was headquartered first in Boulder, CO, and then in Seattle, WA.

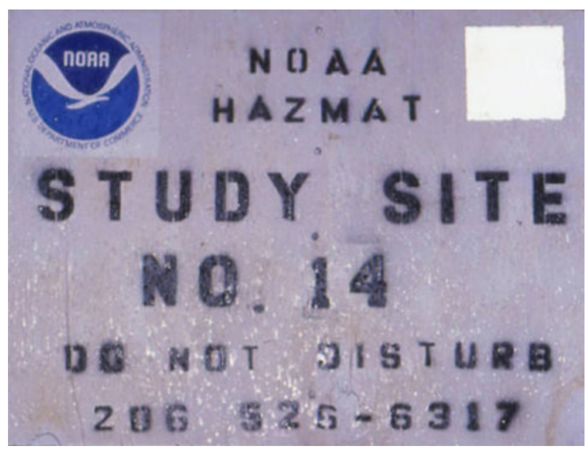


ADM Paul A. Yost, Jr. (center, in front of computer monitor), U.S. Coast Guard Commandant, in the NOAA command post, Valdez, AK, 1989. NOAA photograph.

When the *Exxon Valdez* accident occurred in March 1989, NOAA/HAZMAT fully mobilized for a very large event. At 6:00 a.m. on March 24, the Marine Safety Office in Anchorage relayed a request to NOAA/HAZMAT to estimate the probable path of the oil and identify resources at potential risk. By that evening, six NOAA responders and a NOAA helicopter arrived in Valdez. In the six months that followed, over 30 NOAA spill response specialists would be stationed in Valdez, Seward, Homer, Kodiak, Cold Bay, and Anchorage. NOAA helicopters were deployed to Alaska during the entire first year of field operations. There would be a continuous NOAA scientific support presence in Alaska for nearly the next three years, indicative of the enormous volume of technical information that was generated over the course of the spill response.

NOAA Scientific Support During the *Exxon Valdez*

NOAA's major responsibility during oil spills is to assist the Federal On-Scene Coordinator (FOSC) in understanding all aspects of the complex issues related to containment and cleanup operations. NOAA acts as a liaison between the scientific community and the FOSC during spill responses, distilling technical opinions into concise recommendations upon which the FOSC can make informed decisions.



NOAA study site marker. Alaska State Archives photo.

There is a standard suite of scientific support services that NOAA provides during the early phases of an oil spill response. These include oil overflights and mapping, and trajectory modeling activities. In the *Exxon Valdez* spill, overflights were used both to track oil location, and to provide empirical inputs into the computer models for predicting oil movements. By the end of the summer of 1989, more than 260 overflight maps showing the location and concentration of floating oil had been prepared by NOAA scientists and distributed to the response.

Identification of resources initially at risk from the spill is another service that NOAA routinely provided and continues to support during present day incidents. Environmental Sensitivity Index maps, which show shoreline types, biological resources, and human uses in a given region, had been prepared for Prince William Sound in 1983 and served as general references for areas at risk from the oil and response activities. Then, as now, these maps provided the foundation for state and federal resource specialists to guide response operations in a way that minimized disturbance to wildlife and other resources like salmon spawning streams.

In addition to these basic support functions, NOAA provided technical expertise to a broad range of interagency committees formed by the response to address specific issues. For example, NOAA helped to address special issues like fisheries protection and subsistence seafood safety assessment; management of the large volumes of information that the response generated; investigations of sheen sources and oil amounts; effectiveness of certain cleanup methods; and the feasibility of using chemical shoreline cleaners; among others.

The need for scientific support by NOAA and the other responding agencies during the *Exxon Valdez* response was clear; however, the technical basis for providing that support was often less so. The general physical behavior of oil in the environment was known, but how this oil would interact with this environment and these climatic conditions over a longer period of time was mostly educated conjecture. Oil spill response is a game of tradeoffs, and during the *Exxon Valdez* oil spill, consensus on the evaluation of tradeoffs was rare among agencies and stakeholders.

In 1989, as the first spring and summer of intensive shoreline cleanup came to a close, operational questions remained about the stability of the oil that had not yet been removed from shorelines and whether the notorious Alaskan winter weather would finish the job on its own, alleviating the need for a second year of shoreline cleanup. In the winter of 1990-1991, NOAA shoreline monitoring was used to characterize the status of oil remaining on beaches and to help establish priorities for much larger-scale interagency surveys that would open the shoreline treatment season in 1991.

Finally, the lack of detailed technical information about the longer-term effects of aggressive shoreline treatment was identified by NOAA responders in 1989, when such techniques were routinely employed in Prince William Sound. NOAA response management garnered support both within the response and among the larger response community for using the *Exxon Valdez* incident as a "spill of opportunity" to improve the technical basis for cleaning oiled shorelines.

In the following sections, we will highlight some of the more extensive scientific support activities undertaken by NOAA to help inform cleanup activities—both during the *Exxon Valdez* spill, and beyond.

Winter Studies

In August 1989, NOAA prepared and presented a plan to the U.S. Coast Guard for monitoring the course of recovery and/or re-oiling over the winter of 1989-1990. The plan proposed studying conditions at sites with differing shoreline types, wave exposure, degrees of oiling, and treatment histories. When large-scale cleanup operations ended in late September, 1,068 km of the 1,271 km of coastline designated as oiled in Prince William Sound had been treated; however, only 200 km had been found to require no further treatment. Outside of Prince William Sound, the totals were 3,217 km of 3,951 km treated, and 735 km requiring no additional treatment.

Any hopes that winter storms would substantially reduce shoreline oiling and the need for cleanup in 1990 were dashed as quickly as November, when reports from the field indicated:


NOAA Winter Studies sampling team. Photograph courtesy of Research Planning, Inc.

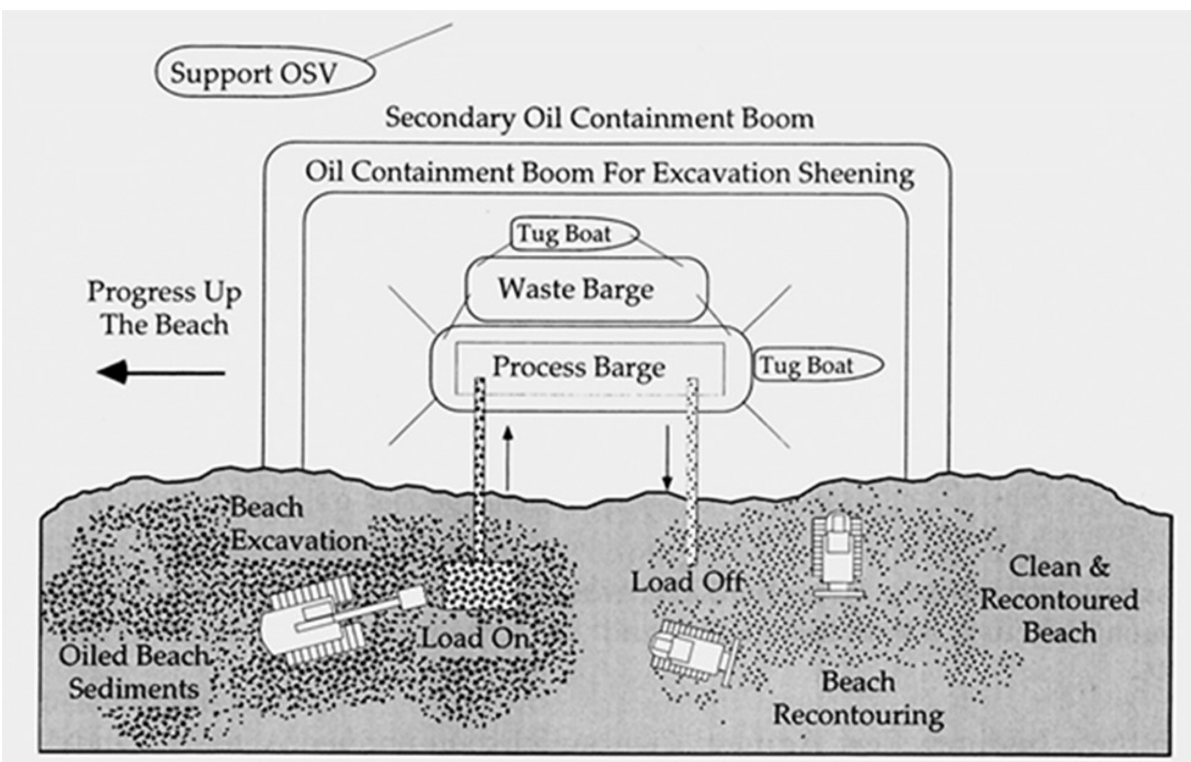
- Surface oil had solidified with the decreased temperatures, but could be expected to re-liquefy in the spring;
- Heavy storms were eroding shorelines and releasing subsurface oil, which in high-energy areas resulted in a reduction in subsurface contamination;
- Re-mobilized oil resulted in localized aggregations of emulsified oil-water mixtures.

In late summer of 1990, NOAA again proposed to the U.S. Coast Guard Federal On-Scene Coordinator that a 1990-1991 winter study plan be enacted, and he directed Exxon to fund the program. NOAA released the results of its 1991 winter surveys in March, emphasizing (as had been the case in 1990) the need to balance the environmental benefits of oil removal with the potential harm to the environment of excessive cleanup.

In this precursor to formal 1991 shoreline surveys and cleanup operations, NOAA opined that two seasons of weathering of the remaining oil and its physical isolation from major resources of concern had reduced the risk it represented to the Prince William Sound system. Treatment recommendations for the 1991 season were therefore relatively modest.

Net Environmental Benefits Analysis: Rock Washing Technology Evaluation

In recognition of the increasing persistence of the stranded oil, as well as the difficulty of cleaning many of the impacted Alaskan beaches due to penetration into boulder-cobble-gravel substrate, the state of Alaska began considering the use of "rock-washing machines" in 1989. In concept, the process would excavate oily sediments from the shoreline, tumble and wash them in specially-engineered machinery, and then replace the cleaned material back on the beach. The state had in fact convened its own evaluation panel and selected a potential design to be constructed, but the high cost (estimated to be a half-million dollars) had stalled the effort.



Plan-view schematic of rock-washing process as proposed for the *Exxon Valdez* response. From U.S. Coast Guard Federal On-Scene Coordinator's Report (1993).

Though unfruitful, the exercise did, however, open discussions about the feasibility of the approach for the 1990 cleanup season among the response agencies and Exxon. The Federal On-Scene Coordinator, RADM David Ciancaglini, requested NOAA to oversee the evaluation of rock washing approaches with other methods, including natural recovery. This "net environmental benefits" evaluation was new for oil spill cleanup, and would result in a new acronym in the lexicon of environmental mediation: Net Environmental Benefits Analysis, or NEBA.

In the NEBA framework, net environmental benefits are defined as the gains in services (the sum total of the resources and processes that are inherently supplied by natural ecosystems) or attained by remedial actions, minus the environmental injuries caused by those actions. Net environmental benefit analysis differed from, for example, environmental impact assessment by the inclusion of potential impacts from the remedial actions. NEBA was the evaluation of tradeoffs associated with cleanup or remediation to determine if the proposed remedial action would be warranted and sufficient.

The apparatus envisioned for use in the 1990 *Exxon Valdez* response was a large, barge-mounted processing plant that received beach material excavated from the shoreline by heavy equipment, transporting it to the barge via conveyor belt. Aboard the barge, the beach sediments would be tumbled and washed, and then returned it to the beach. From the outset, the rock washer appeared to be a formidable engineering effort, as well as being environmentally intrusive. It was, however, considered to be a tool that would be applied in those situations where few alternatives existed.

Prototype Exxon rock washer, July 1989. Alaska State Archives photo.

The NEBA study requested by RADM Ciancaglini and overseen by NOAA was a large and complex evaluation that involved 24 scientists from the state of Alaska, Exxon, and NOAA (including several support contractors). Over a two-month period, it considered engineering issues, evaluation of conditions on the targeted beaches, and anticipated outcomes and impacts of the washing process.

The final report that was issued under NOAA cover in July 1990 articulated the tradeoffs involved in the potential use of the rock washing technique. The final paragraph of the report summarized the issues:

> "Excavation/rock washing is one of the most predictable means of assuring that oil is removed from the environment rather than remaining as a potential source for episodic exposure during winter storms. The expected impacts of the excavation and cleaning process include potential for temporary sheening or resuspension of oiled particulates, creation of silt plumes, and disturbance by equipment and personnel. These impacts can be mitigated by proper containment of sheens and timing of operations to minimize impacts to resources and users. Recreational and some subsistence uses could resume soon after the treatment process. Other subsistence activities would be delayed four to eight years until natural recolonization of intertidal biota occurred."

The report did not recommend a course of action, leaving that decision to the response decision makers. In the end, Exxon and the state of Alaska fundamentally disagreed over the implications of the analysis, with Alaska supporting and Exxon opposing the use of the technology. NOAA essentially cast the deciding vote, stating that there was "no net environmental benefit to be gained by shoreline excavation and washing" and that "this technology has the potential of aggravating the injury to the environment caused by the spill." Based on NOAA's recommendation, the FOSC opted to *not* authorize the project. The state of Alaska was unhappy with this decision, and felt that human use considerations of socioeconomic impact in particular had not been given sufficient weight in the natural science and technology-centric document.

In the formal Coast Guard FOSC report on the *Exxon Valdez* response, the NOAA lead for the NEBA, Dr. Jacqueline Michel, provided insight on the experience:

> "…NOAA's Jacqui Michel…believed that the NEBA process became more a test of which organization would prevail than an exercise in scientific analysis…In hindsight, she felt, the science in the NEBA process may have gotten lost."

The *Exxon Valdez* NEBA was a comprehensive and well-documented process for supporting a decision on the appropriateness of a specific technology and on the level of effort required for implementation. However, the approach was time-consuming, required compilation and interpretation of substantial quantities of engineering and scientific data, and ultimately, the decision was not derived by consensus and as a result, was not universally embraced.

Interestingly, the predictions of oil persistence (in the absence of further treatment) made by the NEBA team in 1990 look, in retrospect, relatively reasonable:

Sheltered parts of Prince William Sound	10+ years
Sheltered outer Kenai	3-5 years
Exposed parts of Prince William Sound	2-4 years
Exposed outer Kenai	1-2 years

In this first use of the NEBA approach, its utility as well as its limitations became evident—lessons which remain applicable to today's responses, a quarter century later. For example, during the *Deepwater Horizon* response, the NEBA approach was used for some of the more difficult decisions encountered in years two and three of the response. As before, however, outcomes and decisions were not without controversy and disagreement—reiterating that the NEBA approach remains a useful tool for assessing tradeoffs…but not a panacea or silver bullet.

Long-Term Intertidal Monitoring: Biology

Removal of large amounts of residual oil from the shorelines of Prince William Sound and western Alaska was an obvious goal of the response in 1989. However, oil changes character as it remains exposed to the elements, and as time passes, stranded oil becomes stickier, more emulsified (i.e., mixed with water), more tenacious, and more difficult to remove. With these changes, the *Exxon Valdez* response considered more aggressive methods, including the use of high-pressure heated seawater, to aid in the mobilization of oil from beaches. Even as early as April, the Coast Guard Commandant had reported to the President that "hot water and steam" would be necessary to clean most shorelines.

NOAA field biologists documenting abundances of rocky intertidal organisms, July 1990. Photo by Gary Shigenaka, NOAA.

Omni-Boom washing shoreline in Prince William Sound, 1989. NOAA photograph.

The vehicles—or more accurately, the vessels—by which this was to be accomplished were impressive hybrid applications of industrial technologies. Boilers and pressure tanks were mounted on barges, and articulated booms for delivering concrete were adapted to pump the pressurized heated seawater through large spray heads to the oiled shorelines. These "Omni-Booms" became key components of the shoreline cleanup and multiple "task forces" were built around the barges and their variants.

As impressive as Omni-Booms were as industrial applications, and as effective as they might have been for removing oil, even a non-biologist might be tempted to ask: What is the view from underneath those spray heads? If the high-pressure hot water is removing increasingly persistent oil from bedrock and boulders, what is it doing to the intertidal communities that live there? If you were a snail, barnacle, or seaweed—was weathered oil really worse than scalding blasts of seawater?

These kinds of questions did occur to NOAA scientific support staff working with the Coast Guard in Alaska. But the mandate to attack the oil spill aggressively came from the top of the spill response hierarchy, vetted by the President. It would require a strong argument, scientific and otherwise, to sway the response away from powerful, if intrusive, shoreline cleanup techniques.

In 1989, such an argument, in the form of research results or a technical report, did not exist. NOAA had no basis for contesting the broad use of high-pressure hot water for shoreline treatment.

With this in mind, NOAA proposed an independent multi-agency-funded intertidal monitoring program to examine the issue of potential impacts from aggressive treatment methods, and in particular, the use of high-pressure hot water. NOAA, the Coast Guard, the U.S. Department of Interior/Minerals Management Service, and the American Petroleum Institute provided funding support to launch the program, which would include components of biology, geomorphology, and chemistry.[2] NOAA already retained contract support for the latter two specialties; biology support, however, was a relatively new addition to the HAZMAT group. A research team that originally had been established by Exxon for shoreline biological assessment work in 1989 was recruited by the new NOAA monitoring program to, in large part, continue the work. The focus would be expanded to include potential treatment impacts, in addition to oil impacts.

The NOAA Long-Term Monitoring Program formally began in 1990. Three categories of Prince William Sound sites were defined for the study: unoiled; oiled and known to have been treated with high-pressure hot water; and oiled and untreated.

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[2] NOAA monitoring would later be supported by the criminal restitution monies paid by Exxon for injuries to fish, wildlife, and lands of the spill-affected region.

The last category of oiled and untreated was a relative rarity in Prince William Sound, as it required agreement across a wide range of agencies, landowners, and interests to, in effect, not clean up an area of known oiling, and leave oil in the environment. These oiled and untreated sites, known as "set-aside" sites, were not easily agreed upon. Ultimately, the NOAA Administrator beseeched the Coast Guard Commandant to intercede. The Commandant was able to extract a promise of bonding for subsequent site treatment from Exxon in the amount of $750,000. Although formal negotiations for set-aside site designation began in 1989, an agreement was not reached until January 1990; and even then, problems were repeatedly encountered with maintaining the untreated status of the designated sites.

Controversy aside, these set-aside sites were critical components of the NOAA Long-term Monitoring Program, and allowed oil effects to be distinguished from treatment effects. Had the set-aside sites not been available, the entire premise of the NOAA program would have been rendered moot and impossible to meet.

Marker sign at Herring Bay set-aside site, 1990. NOAA photograph.

The NOAA monitoring team began fieldwork in 1990 (data would be incorporated from the 1989 Exxon studies). The NOAA Long-term Monitoring Program would continue annual and sometimes biannual field sampling trips to Prince William Sound through 2000. Reflecting the two dominant shoreline types in the Sound, sampling sites included bedrock, boulder-cobble and gravel substrate beaches.

The decade-long duration of this program facilitated a number of insights into oil and cleanup impacts, and subsequently, the nature of recovery on the intertidal shorelines of the subarctic region. These included:

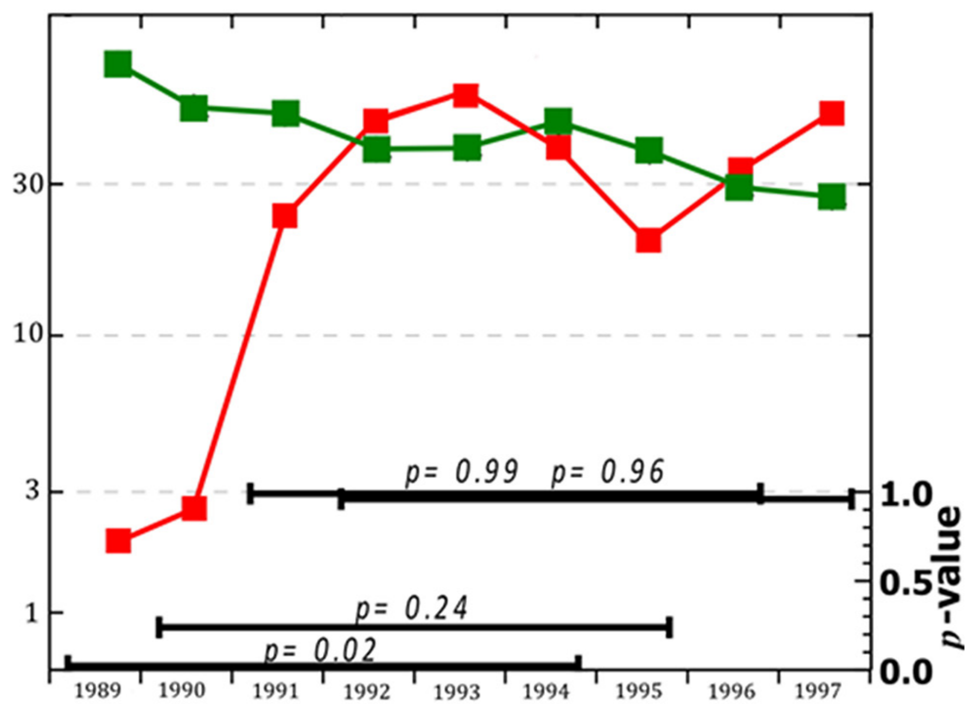
- Observations during the early stages of the spill indicated that intertidal plants and animals were generally resistant to acute toxicity of heavy oil, sometimes surviving 3-4 months of exposure.
- Exposure to high-pressure hot water, however, resulted in 50 to 100 percent mortality of exposed organisms.
- Impacts from high-pressure hot water washing were initially more severe than impacts from oiling alone.
- Longer-term monitoring showed that these differences rapidly diminished with time (1-2 years).
- Intertidal impacts from the spill, whether by oil or treatment, were not evident within 3-4 years.
- Monitoring over the long term, however, documented a high degree in interannual variability in intertidal communities unrelated to the oil spill—but nevertheless very relevant to assessment of oil spills or other disturbances.

Results of the NOAA Long-Term Monitoring Program were released after each sampling cycle, with an initial set of findings in 1991. Although the *Exxon Valdez* shoreline cleanup continued through 1990, and into 1991 and 1992, for that spill the monitoring implications were retrospective in nature—that is, they did not influence cleanup operations already underway. However, the insights about the environmental tradeoffs associated with aggressive shoreline cleanup would be incorporated into subsequent shoreline treatment guidance materials produced by NOAA.

In addition, documentation of the inherent natural variability of biological communities provided design guidance for future disturbance impact monitoring efforts, whether related to spill events or other infrequently occurring phenomena. Very quickly during the initial interpretation of results from the monitoring, it became apparent that variability across study sites and over time would complicate interpretation of the results.

In 1997, with eight years of NOAA monitoring results in hand, a new statistical approach to analysis was designed in collaboration with the University of Washington Center for Quantitative Science. The new analytical framework was termed "parallelism" and acknowledged two fundamental realities of post hoc monitoring of oil spill impact: that unoiled reference sites may be biologically different from oiled sites at the time of impact, thus rendering absolute convergence of conditions in the recovery phase less useful; and that conditions at both oiled and unoiled locations are likely influenced by a host of drivers not related to the spill disturbance.

The parallelism framework was made possible by the availability of long-term datasets in which *patterns* of biological status (in our case, abundance) were compared. Did patterns between impacted and unimpacted sites over time show the same trends? Or was there an influence (e.g., spill effects) that makes the pattern at an impacted site different from an unimpacted site? In this analytical paradigm of spill impact assessment, abundances at an unoiled site may not be the same at an oiled site when a spill occurs; but in the absence of spill effects, both sites should respond similarly to climate, ocean conditions, or other determinants of biological communities in a defined study region.



Parallelism plot for percent cover of rockweed at washed rocky intertidal study sites (red) and control sites, 1989-1997. Significance of differences between six-year trend periods is shown at bottom of graph, e.g., the difference between washed and control percent cover in the 1989-1994 period was highly significant ($p = 0.02$).

Based on the results of the NOAA Long-Term Monitoring Program, we can provide answers to some of the questions it was designed to address.

Have the intertidal biota of Prince William Sound recovered?

Yes, by 1997, the monitoring provided strong inferential evidence that intertidal populations within Prince William Sound experienced a substantial amount of recovery from the effects of the 1989 oil spill and cleanup. The onset of recovery, as defined by a sharp increase in abundance at impacted sites relative to controls, began less than three years after the spill. Recolonization required about one to two years and populations stabilized for most taxa by 1993. During this recolonization, populations increased by a factor of eight on average and the jump was large enough to be detected by statistical tests. The tests quantified temporal parallelism among the abundance time profiles at impacted and control sites within a moving 6-year time window. For most major intertidal assemblages, there was a statistically significant departure from parallelism in the initial 6-year window, indicating that a significant repopulation had occurred at impacted sites relative to control sites. In contrast, time windows that spanned subsequent years showed a high-degree of parallelism, reflecting that the impacted populations had stabilized and had begun to more-closely track fluctuations in control populations.

Having previously noted that Prince William Sound as a whole has *not* recovered, we must emphasize the narrow scope of the NOAA Long-Term Monitoring Program: i.e., it focused on the intertidal shorelines where oil and cleanup were likely to have their greatest direct impact, and relied on a specific definition of recovery (attainment of temporal parallelism) that integrated the substantial natural variability that is the norm in the Prince William Sound intertidal. We did not assess the status of birds, fish, mammals, or many other resources of concern. With our focus and by our metrics, we demonstrated that population abundances, an admittedly gross measure of biological health, had returned to normal ranges of variability within the time frames specified above. We strongly recommend against extrapolation of the results or conclusions beyond their narrow purviews.

The magnitude and scope of the abrupt repopulation events provided compelling evidence that intertidal populations had materially recovered by 1993. Statistically significant repopulation was evident throughout the intertidal zone at both oiled-only sites and hot-water washed sites. Widely disparate intertidal groups, including infauna (organisms that live in the interstitial spaces of sediments), algae, and epifaunal invertebrates (animals that reside on the surface of rocky substrate), began recolonizing at about the same time (1990-1991) and over a similar duration (one-to-two years). While smaller-amplitude perturbations in community structure and abundance continued for some time, most of the recovery from the spill took place during recolonization prior to 1993. Subtle trends within impacted populations were visually evident in time profiles after 1993, but they could be resolved with statistical hypothesis tests based on parallelism with control populations and were investigated in subsequent experimental work discussed in a section to follow.

How did the timing of recovery differ among the various intertidal assemblages and organisms?

Overall, the timing of the recruitment events that were key to the recovery assessment was remarkably similar across the broad range of intertidal flora and fauna. Most intertidal organisms began recovering between 1990 and 1992, although epifaunal invertebrates were early colonizers of the washed sites. Their populations began increasing between 1989 and 1990. For most taxa, sharp increases in population levels ended by 1992, although algal cover in the upper-intertidal zone continued to increase into 1993. The extended recovery within this zone may have resulted from prolonged exposure to oil that persisted along upper transects, but quantitative assessment of such associations was beyond the scope of our rather singular-purposed monitoring.

How did recovery differ at sites that were subjected to high-pressure washing with hot water?

The increase in intertidal populations, as reflected in the amplitude of the post-spill repopulation event, was much larger at sites that were subjected to high-pressure hot water washes. At these washed sites, the average population increase was a factor of eleven, while populations at oiled-only sites increased by a factor of around three.

The most logical explanation for these differences is that damage to intertidal biota was more severe at sites that were cleaned by high-pressure hot-water washes. However, the recovery at these sites compensated, at least in part, for the increased damage. While other oil spill studies at the *Exxon Valdez* suggested that high-pressure hot water washing delayed recovery over oiling alone, the NOAA monitoring and analytical framework indicated that general long-term intertidal recovery occurred at about the same time for both categories of sites.

If intertidal populations had recovered within a few years, why did the monitoring continue for a decade?

There were a number of important remaining issues related to the recovery of intertidal biota after the primary question of recovery times with different treatments was addressed. These issues could only be resolved with continued monitoring, analysis, and as we ultimately decided, with focused experiments.

For example, monitored infaunal populations at washed sites were initially lower than at other sites, and these differences correlated with a deficiency in fine sediments at the washed sites. When the long-term monitoring came to an end in 2000, we established an experiment at Lower Herring Bay to more carefully examine these apparent associations. This experiment will be described in a subsequent section.

There were implications and unanswered questions related to monitoring results from rocky intertidal habitats as well. In 1999, the NOAA intertidal monitoring team helped to establish an experiment in Kasitsna Bay to provide a long-term look at the effects of a singular but intense disturbance to intertidal communities.

The NOAA experience suggests that inherent environmental variability must be accommodated by and integrated into the design of long-term spill monitoring programs. While we trust that all such programs would have, at their core, the desire to distinguish and characterize effects and recovery in the highest resolution and most meaningful way, we feel it is worth noting that accommodating variability could also be used to obfuscate or minimize impact.

Why would anyone wish to intentionally do such a thing? It is not entirely inconceivable that a responsible party might want to show that spill effects are over and that recovery is complete, before others might make that pronouncement. A statistically (although not necessarily ethically) defensible way to do this would be to selectively monitor the most variable physical and biological environments in an affected region, and then show that there is no measurable spill impact above the (exceedingly high) background of natural variability.

For the public, these seemingly are esoteric details of study design that are far down in the "weeds" of environmental research and monitoring; however, these also help to explain at least some examples of the frustrating spectacle of "dueling scientists" in the media and in the scientific literature: one camp making one bottom line claim, and another making precisely the opposite. The devil, indeed, lying in the details.

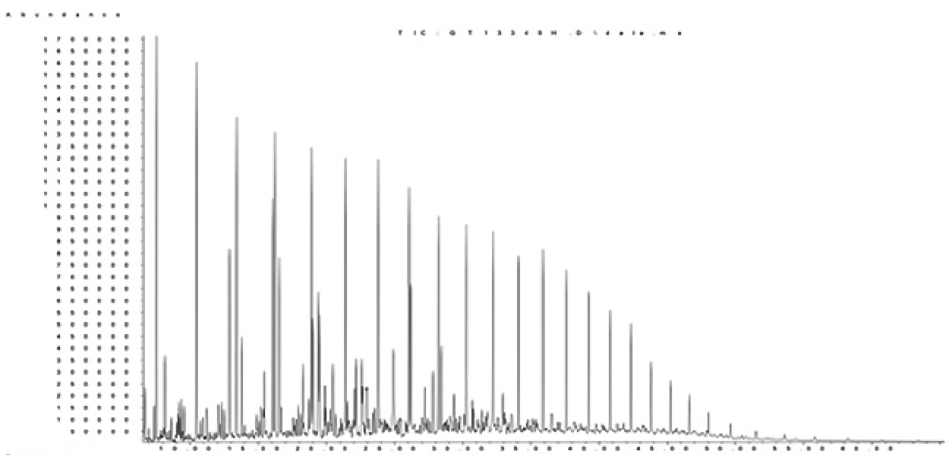
In 2003, the Academy of Natural Sciences of Drexel University—the oldest natural science research institution in the New World—commented on just this sort of competitive science:

> "…uncertainty will remain a fact of life in environmental affairs…policy makers will continue to grapple with decision-making in the absence of facts. It will be all the more important under those conditions to distinguish between high quality data, and data that has been selectively acquired to advance advocacy agendas. In a democratic society, both types of data are important, however, it is equally important that they not be confused."

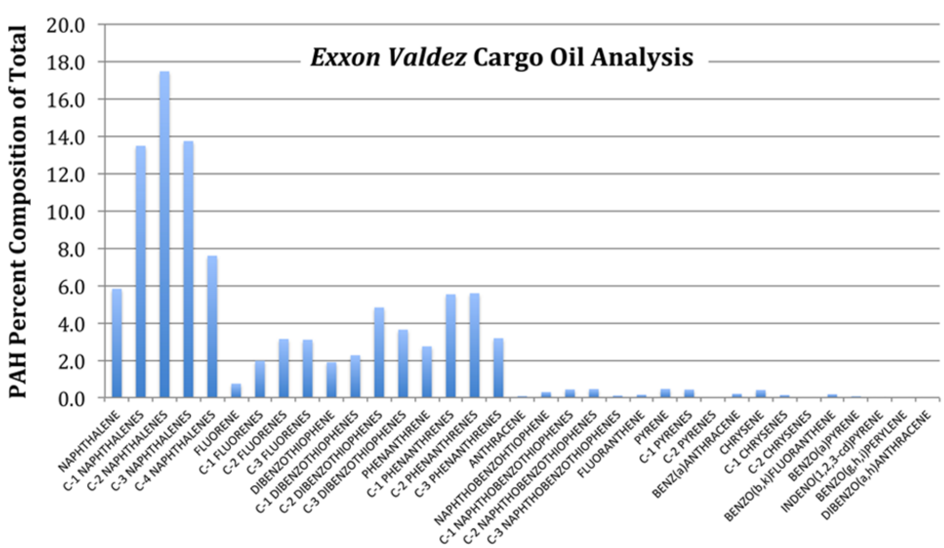
The sinister hypothetical example aside: we can hope that the overwhelming majority of spill monitoring practitioners will have the earnest goal of understanding oil and response impacts in the clearest and most relevant way possible. The NOAA monitoring program was adapted midstream to accommodate the high degree of variability encountered and offers one example; there are many other approaches that lend themselves to showing impact and recovery in this kind of setting.

Long-Term Intertidal Monitoring: Chemistry

As would be expected from assessment and monitoring studies related to an oil spill, chemistry was an integral feature of NOAA scientific support during the *Exxon Valdez* response. Chemical analysis provided the technical basis for answering the question, "What was spilled?" In this case, the general answer was Alaska North Slope (ANS) crude oil. But ANS—like all other crude oil "flavors"—is not a static mixture. It is basically a blend of crudes from several different fields on the North Slope of the Alaskan Arctic, around 1,000 km north of Valdez. The major constituent fields include Prudhoe Bay, Kuparuk, Lisburne, and Endicott. Therefore, not all ANS crudes are alike.



Total ion chromatogram for Alaska North Slope crude oil, showing the separation of the crude oil mixture into discrete components. In the gas chromatography-mass spectrometry method employed for oil analysis, compounds separated by gas chromatography are then identified and quantitated by mass spectrometry.

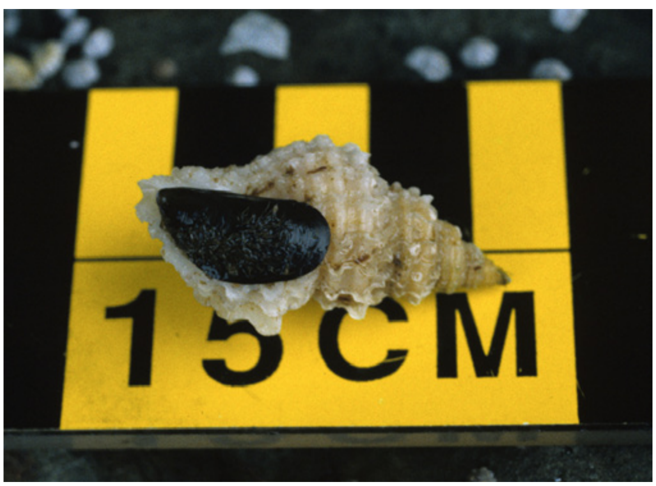


Polynuclear aromatic hydrocarbon (PAH) analysis of *Exxon Valdez* cargo oil. Source: Institute for Environmental Studies, Louisiana State University.

The chemistry of crude oils determines their behavior in the environment. ANS crude blends tend to emulsify (i.e., mix with water) quickly, forming a stable emulsion—or "mousse." The tendency and rate of emulsification of spilled ANS is known to be accelerated by wind mixing, and is thought to be related to the blend's wax content.

An estimated 15-20% of ANS crude oil evaporates in the first 24 hours of a spill—a figure that surprises many because the overall volume of spilled oil only seems to increase with time. This perception can be attributed to spreading of the oil, and the emulsification process described above, which increases the apparent volume of an oil spill: weathered oil can form a stable mousse with up to 75% water content (thereby increasing the slick volume four-fold).

Chemistry of oil sampled in the environment can confirm its source, determine its state of weathering, help to predict subsequent fate, and can provide a quantitative measure of contamination. NOAA chemistry support relied on gas chromatography-mass spectrometry methods to facilitate discrimination and quantitation of aromatic hydrocarbons (AHs) in oil (AHs are a major constituent of crude oil and are frequently targeted by environmental chemists because they have been linked to a number of toxicity effects). In the first year of the *Exxon Valdez* oil spill, U.S. Coast Guard and NOAA support chemists from Louisiana State University analyzed more than 800 samples of oily debris, tar balls, oily water, beach substrate, and animal tissues in order to answer specific questions about oil contamination. For example, tissue samples from dead gray whales found on beaches in the path of the spill were analyzed to determine if oil contamination was present (it was not).



Caught in the act: a drill (*Nucella lamellosa*), preying on a blue mussel (*Mytilus trossulus*), 1993. Photo by Gary Shigenaka, NOAA.

Beginning in 1990, coincident with biological shoreline monitoring surveys undertaken by NOAA, a wide range of intertidal animal tissues were also collected and analyzed. Beach sediments were collected, but were limited to gravel or finer-grained material that could be easily sampled (i.e., no boulders). Organisms were also collected as part of the routine sampling that took place during the monitoring field work. Targeted intertidal invertebrates included mussels (*Mytilus trossulus*.); periwinkle snails (*Littorina* spp.); drills (*Nucella* spp.); and sea stars (*Pycnopodia helianthoides*).

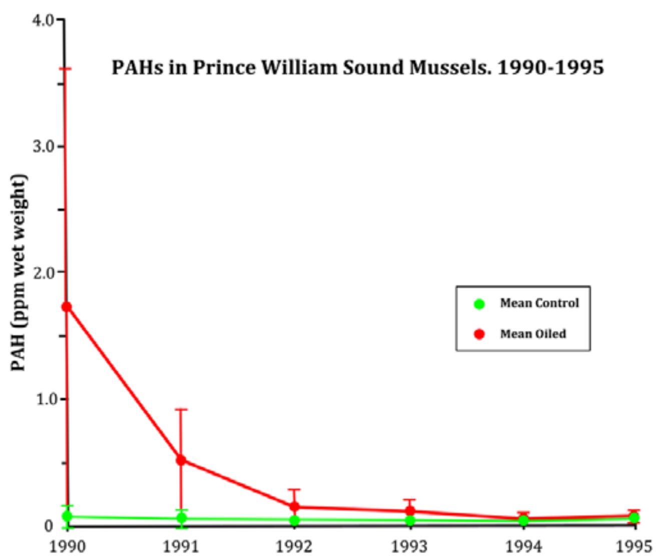
Although we typically see pictures of very heavy oiling when a spill occurs, shoreline oil contamination is notoriously patchy in its distribution—with respect to surface contamination only. Add in the third dimension of oil penetration into porous beach substrate (such as is the norm in Prince William Sound), and the stage is set for several sampling challenges.

Initial sediment chemistry sampling in the 1990 NOAA Long-Term Monitoring Program resulted in 49 collections at different tidal elevations from 18 sites. The concentrations of total (summed) AHs were highly variable, ranging from a high of 64 parts per million (ppm) in Northwest Bay, to a low of 0.00009 ppm in Outside Bay. An interesting and intuitive—but not statistically significant—trend showed higher sediment concentrations in upper tidal elevations of untreated sites and much lower levels in the lower intertidal zone; and the opposite situation for washed sites.

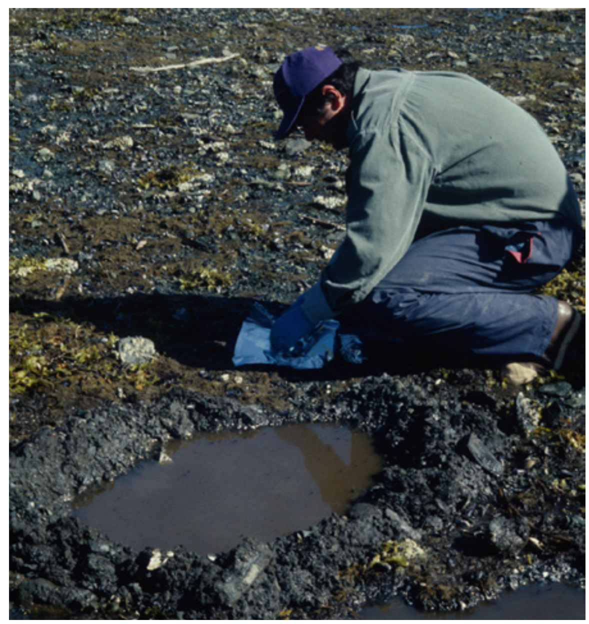
Invertebrate tissue AH concentrations also spanned a wide range in 1990, from below detection limits to a maximum of 82 ppm dry weight measured in a mussel sample collected at Smith Island. By far, mussels had the highest average body burdens of AHs of the four animals sampled, 3.9 ppm (periwinkles 0.7 ppm, drills 0.5 ppm, sea stars 0.2 ppm). Broken out by site treatment category, tissue concentrations for all four invertebrates were highest at sites treated with high-pressure hot water.

Mussels are considered to be an important "sentinel" organism, and they had been used for monitoring the biological availability of a wide range of contaminants, particularly hydrocarbons, in coastal monitoring programs for over two decades before the *Exxon Valdez* spill. Because they are filter feeders, mussels were considered to integrate contamination in the water column and associated with floating particulate material, and, more so than measurements in sediments and water, tend to average out variable environmental conditions.

Due to high analytical costs, low measured concentrations, and (in the case of drills) collection impacts to surviving populations, collections for chemistry were limited to mussels in 1992. However, native littleneck clams (*Protothaca/Leukoma staminea*) were added in 1991 because of their importance as a subsistence resource, prey items for wildlife like sea otters and shorebirds, and because of their close association with potentially contaminated beaches.



Mean values of polynuclear aromatic hydrocarbons (PAHs) in mussel tissue over time from oiled and control sites with 95% confidence limits (the two groups were significantly different through 1992, Mann-Whitney U test, p=0.05).



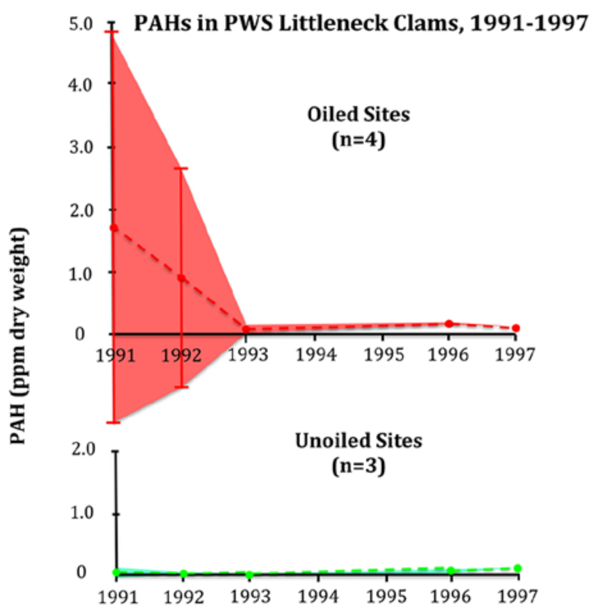
Field chemist sampling littleneck clams, Bay of Isles, 1999. Photo by Gary Shigenaka, NOAA.

Tissue chemistry results for mussels collected at oiled sites in the first six years of NOAA monitoring showed a steady decrease with time. By 1993, there was no statistical difference between mussel contamination at oiled sites, and that at unoiled sites.

Native littleneck clams showed a similar pattern of relatively high concentration at oiled sites when the sampling began in 1991, followed by a steady decline until hydrocarbon levels were essentially equivalent to control sites and approaching limits of detection. The table on the next page provides mean and standard deviation results for all clams sampled in each year, and shows that by 1997, tissue levels were statistically equal at oiled and unoiled sites. The figure shows clam tissue concentration results for a smaller but consistently sampled set of sites and suggests an even earlier convergence, in 1993 or 1994.

Summary results and Mann-Whitney U test results for total target aromatic hydrocarbons in all sampled littleneck clam tissues, 1991-1997. Values in ng/mg, dry weight. Results unavailable for 1994 and 1995.

	1991	1992	1993	1996	1997
Oiled Mean	1.05	1.37	0.20	0.15	0.07
Oiled Std. Dev.	1.79	3.07	0.16	0.16	0.06
Oiled N	12	25	9	8	7
Unoiled Mean	0.11	0.03	0.02	0.04	0.03
Unoiled Std. Dev.	0.08	0.01	0.01	0.02	0.02
Unoiled N	5	3	3	5	5
Mann-Whitney p value	0.0114	0.049	0.0265	0.0277	0.3701



Total target aromatic hydrocarbon results for clam tissues at standard (consistently sampled) NOAA/HAZMAT monitoring sites, 1991-1997. Shaded area represents 1 standard deviation around mean values for sites. Values in ng/mg (ppm) dry weight.

By 1999, hydrocarbon concentrations in mussels and clams were uniformly low. Although only 12 sediment samples were collected, four of these contained relatively higher concentrations of 1.5-7.5 ppm; however, sediment-sampling sites were not randomly distributed and in fact were focused on areas of known contamination (e.g., a heavily oiled tidal marsh in the Bay of Isles).

Interestingly, of 29 total samples, the lowest mussel total PAH concentration measured was at the Smith Island site where the highest spill-related tissue level was recorded in 1990 (0.027 ppm vs. 82 ppm). And a little ironically, the highest mussel tissue concentration in 1999, 2.5 ppm, resulted from a sample we collected from the docks in the Cordova small boat harbor before we departed on our field excursion, and was unrelated to the oil spill.

Sixteen sites were sampled for native littleneck clams in 1999, and all sixteen were uniformly low in tissue concentrations: 0.03-0.05 ppm.

Source fingerprinting analysis was performed for the 45 mussel and clam samples; however, 44 of the 45 bivalve samples collected in 1999 were below levels required for chromatographic fingerprinting. Chemists at Louisiana State University compared PAH profiles in tissues with that for Alaska North Slope crude oil, and based on pattern analysis determined that *Exxon Valdez* petroleum hydrocarbons could be distinguished at eight sites; a hydrocarbon fingerprint consistent with diesel or light fuel oil was much more prevalent, and was determined for 26 sites.

In 2006, NOAA commissioned an independent chemistry review to provide lessons learned from long-term monitoring. It had many criticisms and recommendations. Chief among these was the observation that the study design for chemistry was *ad hoc* in nature and provided few opportunities for easy longer-term time series analyses. This was undeniably true and was no doubt frustrating from the perspective of making sense of the huge amount of data generated from more than a decade of sampling. However, certain fundamental aspects important to the response were nonetheless addressed: oil fingerprinting, short-term weathering changes, bioavailability, tissue concentration trends, among others. Nevertheless, the recommendation to allocate greater thought and effort into program design is applicable to monitoring in general, not just the chemistry component.

The 2006 review did confirm the utility of bivalve mollusks like mussels as sentinel organisms:

> "From our experience, nothing beats the convenience of mussels…easy to collect and very efficient filter-feeder species. Sample integrity is enhanced when, if frozen soon after collection, they become self-contained shipping containers that arrive intact and uncontaminated at the laboratory. Any other macro-bivalve would likely also suffice (e.g., *Protothaca*, *Mya*, *Saxidomus*, *Macoma*, *Clinocardium*, *Mactromeris*, *Siliqua*, or *Hiatella*) but …drawbacks regarding comparability of uptake (are not known). For example, from the oil profiles, *Protothaca* definitely does something different than *Mytilus* (they accumulate from 5 to 10 times less PAH from the same area) but (it is unknown) if this is a physical or physiological difference."

As was noted in the chapter on the toll of the spill, pockets of lingering oil remain at a few locations in Prince William Sound, and 25 years later, it is surprising that they have persisted in a relatively unweathered state. In 2007, a team of scientists led by chemists from the NOAA/NMFS Auke Bay Laboratory calculated the rate of loss of the remaining oil in the Sound and the Gulf of Alaska and determined that the rate had declined from around 68 percent per year before 1992, to around 4 percent per year after 2001. The chemistry of residual oil revealed that many of the compounds normally quickly biodegraded by microorganisms (i.e., *n*-alkanes) were still present—a finding the researchers termed "remarkable." They suggested that emulsification of the oil and viscosity changes during the initial stages of the spill may have inhibited the expected weathering processes.

The 2006 NOAA chemistry monitoring review supported these findings:

> "…we now realize that the oil removal and weathering issue is just not as simple as we first believed…an exposed beach (receives) more energy to remove its oil through physical dissipation. But after that, the easy-to-remove deposits are gone and things get subtle. The general exposure of a beach may be shadowed by obstructions…or may have impermeable substrate layers…that block the bottom of an oil layer (allowing it to pool), or during accretion cap the top of an oil layer (protecting it from dispersion) or if permeable, saturate the interstices and preserve the buried oil…Thus, 17 years later, we are still finding fresh pockets of oil (albeit minute relative to the original spatial coverage but still a local chronic source of exposure)."

Recent studies (2013) along the rocky coast of national parks in the Gulf of Alaska—much farther from the primary impact areas in Prince William Sound—also located pockets of persistent oil on boulder shorelines. Chemical analysis of the oil residues by the NOAA/NMFS Auke Bay Laboratory and the Woods Hole Oceanographic Institute using newer analytical methods (two-dimensional gas chromatography) confirmed that at least some of this remnant oil was only slightly weathered—again surprising us with counterintuitive findings more than two decades after the spill.

Long-Term Intertidal Monitoring: Geomorphology

Geomorphology is the study of landforms and the processes that form them. Coastal geomorphology, as its name implies, refines the focus further to the dynamic margin between the land and the sea. Spill responders are very interested in geomorphology as it relates to the behavior of oil at the land-sea interface, as it determines how the oil comes ashore, where it will be stranded, and how complex cleanup of oil will be.

The oil-impacted shorelines of Prince William Sound proved to be both challenging and enlightening for coastal geomorphologists supporting the *Exxon Valdez* spill response. The gravel beaches that are common in Prince William Sound presented special problems that had not been previously encountered at a

Geomorphologist assessing oil penetration on boulder-cobble shoreline in Prince William Sound, 1989. Photo by Research Planning, Inc.

Earthquake ghosts: remnant subtidal clam bed, uplifted well above the high tide level at Crab Bay monitoring site, 2006. Photo by William Driskell.

major spill: many of the shorelines had been relatively recently uplifted (as much as 9 m) in the 1964 Great Alaskan Earthquake, and within the Sound itself, they were sheltered from full exposure to the elements, particularly to the wave action that is a primary physical determinant of coastal geomorphology. The gravel beaches in Prince William Sound are considered to be "intermittently exposed," meaning that waves big enough to move the gravel around occur at irregular intervals.

The previously described operational monitoring (i.e., Winter Studies Program) determined the persistence of the oil, chemically characterized the residual oil, and forecasted the degree and distribution of shoreline contamination. When the NOAA Long-Term Monitoring Program was designed and implemented, it made sense to both include a component of geomorphology, and to continue the studies that had been originally begun in support of the response. While the core original study sites were retained in the continuation of geomorphological studies, a concerted effort was made to overlap at least some of the biology study sites. In addition, field work was expanded to include sites on the outer Kenai Peninsula.

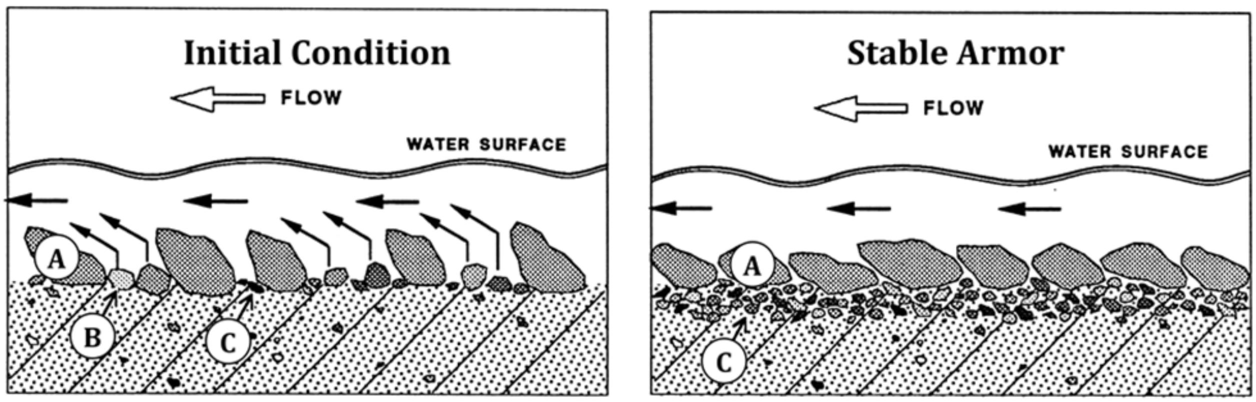
Shoreline types in Prince William Sound had been surveyed by NOAA's Environmental Sensitivity Index mapping teams in 1983, and the results of those surveys showed a predominance of three generic shoreline types: mixed sand and gravel, and gravel beaches (41 percent); sheltered rocky coasts (30 percent); and exposed rocky platforms (23 percent). The study sites chosen for geomorphology studies were representative of the first two of these major shoreline types, where oil was most likely to persist.

The glamorous side of geomorphology: assessing oil penetration at Herring Bay, Knight Island, July 1994. Photo by Alan Mearns, NOAA.

It should be noted that the geological definition of "gravel" includes any coarse-grained sediments that can be moved by waves. As a result, "gravel beaches" are those with sediments from granules that are 2-4 mm to boulders greater than 256 mm.

The prevalence of gravel beaches in Prince William Sound and other parts of the spill-affected region presented shoreline assessment and cleanup problems for the response, as oil readily penetrated the permeable substrate, could be additionally buried by the build up of berms, and was subject to formation of hardened asphalt pavements over time. The oil penetration through porous beach material and the tendency of gravel to accrete have been factors in the lingering oil that continues to be observed 25 years later.

An additional consideration identified by the NOAA geomorphology team was the presence of a stable layer of "armoring" on the surface of the middle and lower intertidal portions of gravel beaches in Prince William Sound. The formation of surface armoring had been described for river gravel bars, but had not been known in coastal marine settings. In this process, currents remove smaller-sized sediment fractions at the beach surface, leaving larger material that effectively forms a coat of armor that shields underlying beach sediments from reworking by wave action—and underlying oil from removal by normal weathering processes. Therefore, oil buried beneath an armored surface would tend to remain for a longer period of time than oil buried on an unarmored beach.



Development of an armored surface of coarse material on a gravel beach. Particles of size A are too large to be removed by currents, those of size B are readily transportable, and those of size C are sheltered by the larger particles and not moved by currents. C particles are on the order of 1.5 to 5 x smaller than A particles. From Michel and Hayes (1991).

As part of the 1991 NOAA geomorphology study, the viability of the technique of "berm relocation" was evaluated as a response approach. Berm relocation was operationally defined as the "movement of oiled sediments from the inactive beachface areas into the upper intertidal zone, where they could be treated and reworked by wave action." The method was not a small undertaking and required the transport of heavy earthmoving equipment to the shoreline.

Berm relocation on Northeast Latouche Island, 1990. Photo by Gary Shigenaka, NOAA.

Aerial view of berm relocation activities at Sleepy Bay, 1990. Photo by Gary Shigenaka, NOAA.

Although Exxon's evaluation of the method concluded that it was very effective in facilitating removal of subsurface oil by natural processes, and that "…all the sites have been restored to pre-treatment morphology with no net loss of sediment," NOAA's study of the issue did not arrive at the same conclusions, citing in particular the conditions at one extensively monitored and aggressively berm relocated site at Point Helen.

The differing conclusions appeared to stem from the degree with which beach crews implemented the berm relocation. The NOAA team observed that if only the face of a storm berm, or only spring or neap berms[3] were excavated and the sediment was carefully placed in the upper intertidal zone, the result was rapid cleaning of the sediments by wave action and rapid recovery of the beach profile to its original configuration, in a few months at most. However, if the excavation was carried out in a more aggressive way, with the destruction of all high-tide berms and massive volumes of sediment moved lower than the upper intertidal zone, recovery was much slower and took much longer (more than a year). The NOAA geomorphology team nonetheless acknowledged that subsurface oiling in the footprint of the excavated area was effectively removed. Any subsurface oil lower in the intertidal zone was not affected; in fact, it could be buried deeper by the relocated sediments.

NOAA concluded that the technique, while effective at reducing oil, also had potential downsides of extended physical recovery, and, in more developed areas, enhanced erosion attributable to the loss of the shoreline protection properties of berms. In 1992, the issue was revisited and the conclusions were reaffirmed and strengthened with the finding that at the most aggressively restructured sites, sediments had not stabilized. In addition, the frequency and magnitude of constructive wave activity was found to be an important determinant for transport of finer-grained material back up the beach.

Finally, the NOAA geomorphology team documented that given one additional storm season, the high tide berms of a study location that was not berm relocated was cleaned by natural reworking of upper intertidal sediments.

The geomorphology component of the NOAA Long-Term Monitoring Program enabled insights into the influences of natural processes like winter storms and human actions like berm relocation on the amount of oil contamination remaining in a shoreline after four years and beyond. While each shoreline type had its own profile, the effort represented the most comprehensive documentation of beach physical features and oiling conditions with time.

The *Exxon Valdez* experience in Prince William Sound underscored the geomorphological complexity of gravel beaches, and suggests that other areas where such intermittently exposed shorelines predominate—like the Arctic—will likely present significant challenges for oil spill response. If the substrate and currents support the formation of an armored layer (a process still not well understood), as was the case in Prince William Sound, heavy oiling can remain in place for decades.

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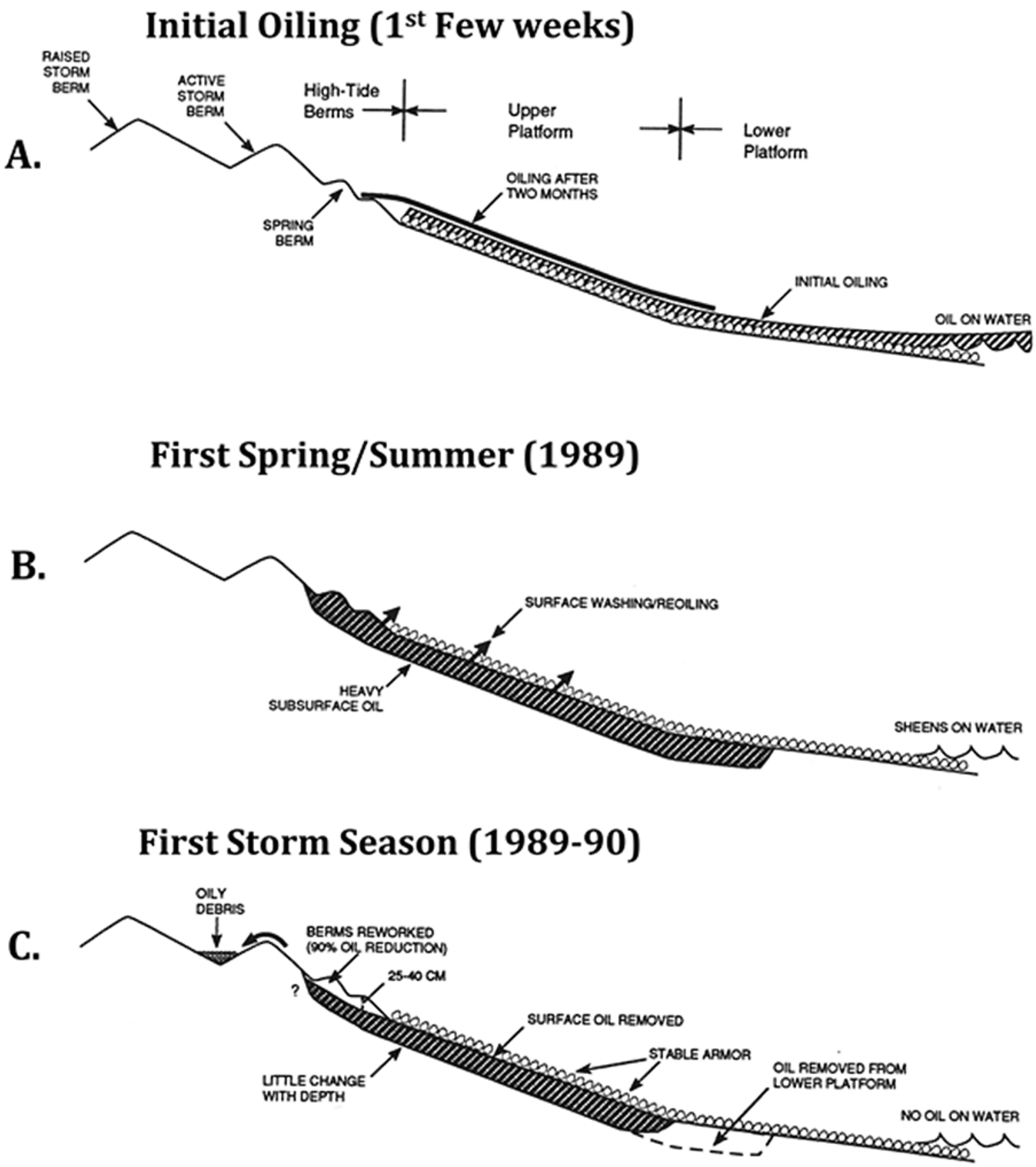
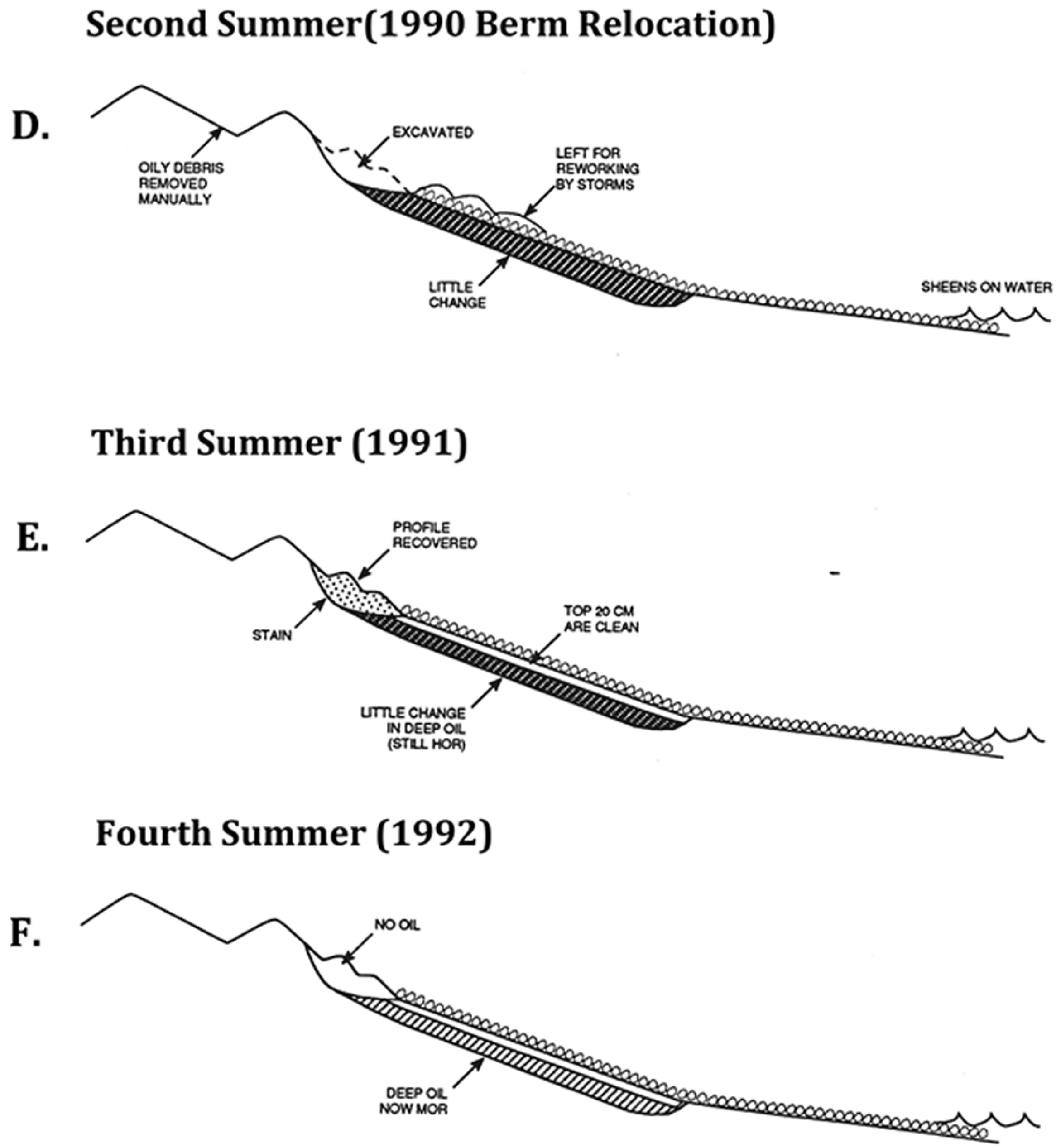
[3] During neap tides, wave runup is unable to overtop the pre-existing berm crest, resulting in the accumulation of sediment lower on the beach face in what is termed a 'neap-berm'. At spring tide, the sediments composing the neap berm are transported onto the top and over the crest of the higher spring berm.



Schematic model of the behavior and persistence of *Exxon Valdez* oil on an armored coarse-grained gravel platform from the initial stranding (1989) through the first storm season (1989-90). From Michel and Hayes (1993).



Schematic model of the behavior and persistence of *Exxon Valdez* oil on an armored coarse-grained gravel platform from the second summer when berm relocation takes place (1990) through the fourth summer (1992). HOR = heavy oil residue; MOR = medium oil residue. From Michel and Hayes (1993). Note that berm relocation was effective at removing the oil in the excavated area but not lower on the beach.

NOAA Experimental Studies 1999-2013

The NOAA Long-Term Monitoring Program answered one set of important questions related to intertidal recovery and provided the basis for operational spill response guidance. More specifically, the monitoring program documented that the widespread use of high-pressure hot water resulted in a greater degree of intertidal damage than was caused by oil alone; but generally within three to four years, the differences in impacts between washed and unwashed sites had diminished; and in fact, biological recovery on the shorelines was either well underway or complete. Operationally, these findings were distilled to the question of whether the necessity/value of removing more oil from the environment was worth the tradeoff of more severe initial intertidal damage that would subside after a few years. In this way, the NOAA Long-term Monitoring Program provided the basis for enhanced spill response guidance during subsequent incidents.

In addition to addressing the underlying operational question about the impacts of spill response *vis-à-vis* oil, the large-scale monitoring raised other questions and hypotheses related to the nature of recovery after a disturbance. For example, did aggressive treatment disrupt the physical environment to the extent that biological recovery was delayed? What were the significant preconditions and drivers for recovery following a severe disturbance in the intertidal? Did the disturbance of oil and cleanup initiate distinct patterns of succession over time in the intertidal communities? Could the trajectories of recovery noted in the long-term monitoring be replicated in more tightly controlled experiments?

As the long-term monitoring wound down, NOAA transitioned to a set of opportunistic studies and experimental investigations that focused on some of these questions arising from ten years of study of the *Exxon Valdez* spill impacts.

Mearns Rock and Landscape-Scale Photo Monitoring

The old adage, "A picture is worth a thousand words," is not often cited by scientists studying the environmental effects of a major disturbance. But in 1990, NOAA ecologist Dr. Alan Mearns began a photographic journey that would not only alter how we view and value "snapshots," but also how we consider and account for natural variability in assessments of impact and recovery.

As we have previously described, from 1990 to 2000, NOAA's Emergency Response Division led an annual effort to quantitatively monitor the abundance and diversity of intertidal marine life on selected oiled, oiled and washed, and unoiled reference shorelines in Prince William Sound. The results showed that recovery for the most prominent species occurred within three to four years of the spill. This conclusion required careful consideration of year-to-year variations that were occurring naturally at *all* study sites, including unoiled reference sites. The program determined, among other things, that monitoring over a longer-term was necessary to define the natural range of variability in the Prince William Sound environment, and then to establish the characteristics of impact and recovery within that range and timeframe.

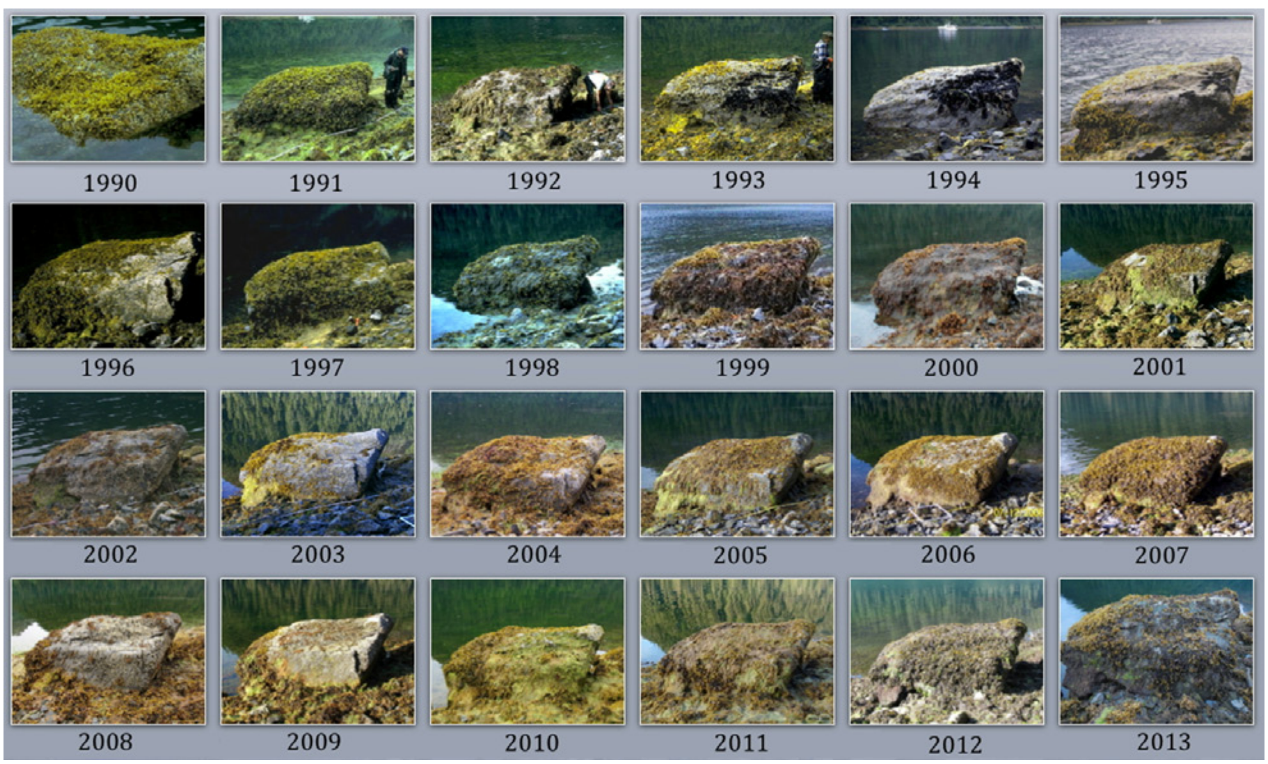
During the fieldwork for the long-term monitoring, Dr. Mearns collected copious—and some at the time felt, excessive—numbers of photos and videos of both the activities and the site conditions. As he and the other members of the NOAA monitoring team returned year after year to the same study sites, this photo documentation began to morph into a time series that visually displayed the variability that would be captured in quantitative fashion by the monitoring data.

One location in particular, along the northern shoreline of Snug Harbor on Knight Island, stood out among Alan Mearns' several million photographs. It showed a Volkswagen-sized, potato-shaped boulder in the middle intertidal zone of the NOAA monitoring site. The slightly obsessive attention paid to this boulder by the NOAA Senior Scientist over several years of monitoring visits resulted in it being dubbed, "Mearns

Dr. Alan J. Mearns, with Mearns Rock , July 2006. Photo by Jeff Lankford, NOAA.

Rock." This seemed appropriate: another famous piece of geology, Plymouth Rock, was probably less photographed over three hundred years of American tourism than Mearns Rock had been in only a few cycles of NOAA shoreline monitoring.

As the time series of Mearns Rock images grew with each successive year's photograph, the portrait of interannual small-scale intertidal variability became apparent. Snug Harbor had experienced oiling in 1989, and Mearns Rock was situated in a treatment area but not far from an untreated "set-aside" site (refer to the previous discussions concerning the role of set-aside sites in monitoring impacts). However, visible oiling had diminished at the study site, and even at the untreated set-aside site within two years. As the Mearns Rock time series grew to five, ten, twenty years and more, the variability captured in the annual photo was unabated.

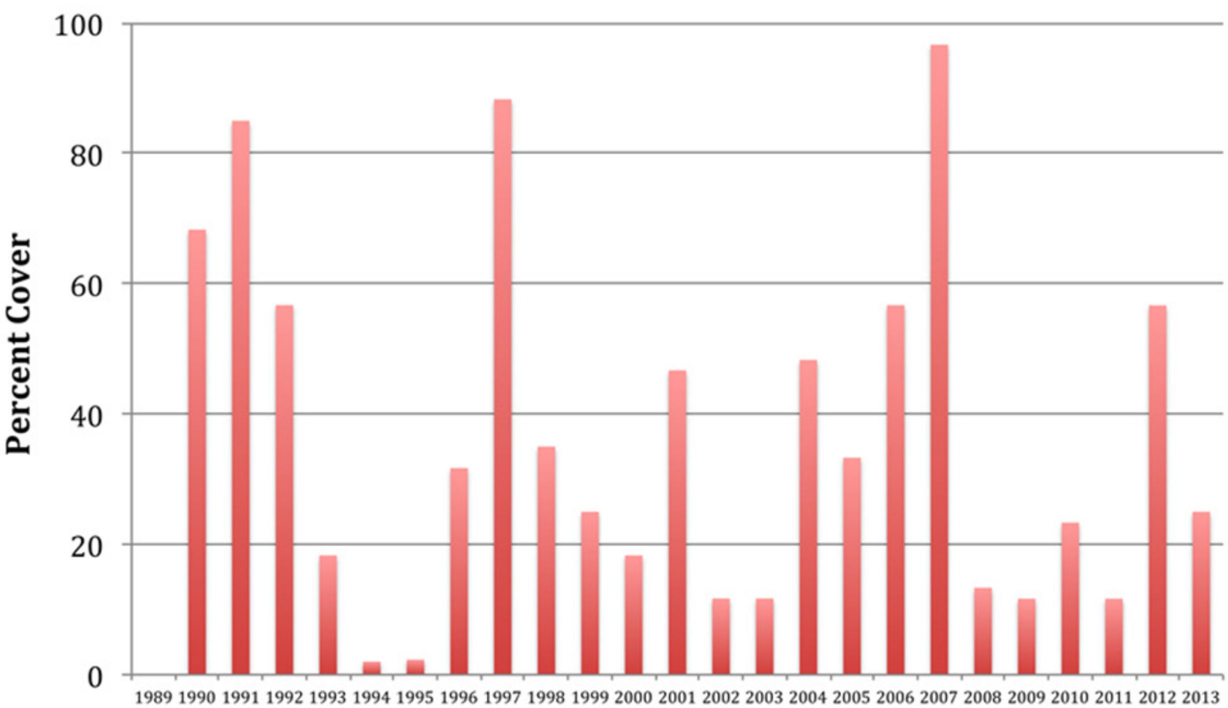


Mosaic of 24 years of Mearns Rock photos, 1990-2013. Courtesy of Alan Mearns, NOAA.

Dr. Mearns had also initiated photo time series at other NOAA monitoring locations as well, and in 2001 he began a similar series at the site of a large landslide in Lower Pass that had apparently been triggered by an earthquake the previous year. The landslide provided an unanticipated opportunity to monitor the colonization of virgin bedrock and boulder substrate that had been moved into the intertidal zone by the slide. This represented a "bonus" site for augmenting the data for unoiled reference sites and would prove to be an important addition to the suite of locations monitored by Dr. Mearns in the years to come.

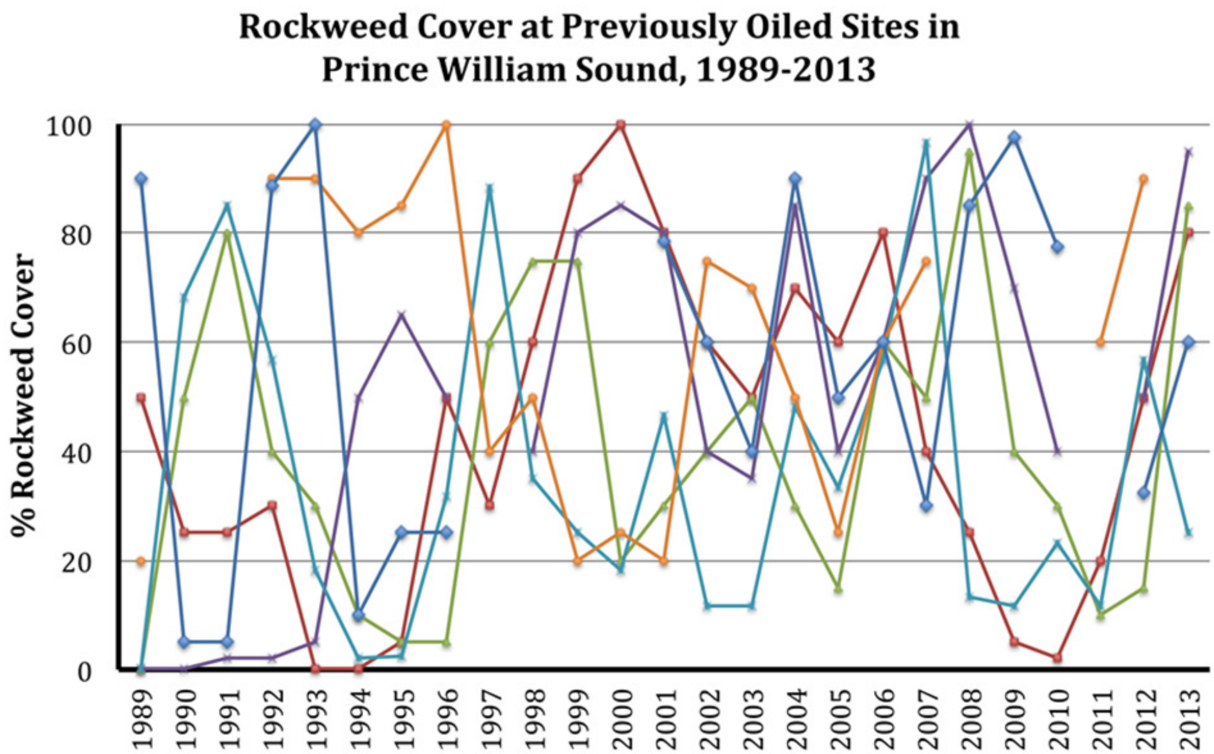
The photo time series of Mearns Rock and the other documented sites in Prince William Sound conveys year-to-year variability intuitively and effectively. To capture conditions in a semi-quantitative fashion, the percent cover of seaweeds and mussels on the face of Dr. Mearns' boulder and the intertidal zones of other sites was estimated for each year's photograph. While the conversion of information captured in photographs permitted additional comparisons, the range of variation from year-to-year and over the period of a few years remained apparent. As shown below in the plot of percent rockweed (*Fucus distichus*) cover estimated derived from the photographs of Mearns Rock, values jumped from nearly zero in 1994 and 1995 to nearly 90 percent in 1997. In contrast, nearly complete rockweed cover in 2007 plunged to less than 20 percent the following year.

Large rockslide along Lower Pass, Prince William Sound, July 2000. Photo by Gary Shigenaka, NOAA.



Cover of rockweed (*Fucus distichus*) estimated from face of Mearns Rock, 1990-2013. Compare to photo mosaic on the previous page.

Recalling that the NOAA Long-Term Monitoring Program had integrated the assumption that shoreline biological communities at different locations within a geographic region might be expected to respond similarly over time to physical and climatic conditions, one might anticipate that the Prince William Sound photo time series and the biological measures estimated from them might reflect parallelism of percent cover trends with time. The raw data do not, however, and seem to convey a greater degree of randomness.



Variations in percent cover of rockweed at six previously oiled long-term photo-monitoring sites in western Prince William Sound, 1989-2013.

This, perhaps, reflects the limitations of the Mearns Rock photo-monitoring approach: while "sampling" is relatively easy and requires primarily a dogged persistence, the results remain primarily visual and can at best yield only semi-quantitative metrics. Because of this, analysis, interpretation, and certainly, extrapolation are restricted to very general terms. On the other hand, photographs communicate conditions of variation and change in a highly effective way, and for many, in a more easily digested form than a "spaghetti plot" like that shown above for rockweed cover at multiple sites; or a table of values over time.

The inherent variability of the environment has implications for oil spill response and assessment. Clearly, the amount of intertidal injury that occurs during a spill and cleanup, and the trajectory and rate of recolonization, depend on the actual health status of a community at the time of an incident. If we use simple metrics like abundance or cover to reflect robustness of a resource of concern, then it will significantly affect our assessments of impact and recovery if the event occurs during a period of (for example) high mussel and/or seaweed cover, or during a period of low cover.

The actual factors or causes responsible for high or low biological cover or abundance will be of less direct importance for operational scientific support for oil spill response than the usual issues of oil transport, fate, and short-term effects. Understanding how much of an observed effect can really be attributable to an oil spill, and how much might be the expression of a large but subtle natural influence would be critical for impact assessment, recovery projections, and restoration planning.

The simplicity of the photo-monitoring approach has been discussed here as a shortcoming with respect to the analytical limitations possible and appropriate with results. That simplicity, however, is also a significant strength. In contrast to other environmental assessment methods, including those used for the other NOAA monitoring and research activities that took place for the *Exxon Valdez* oil spill—in which highly specialized training and skills were a prerequisite—photo-monitoring requires only a modest ability to take digital photographs.

Alan Mearns (center) orienting volunteers assisting in photo-monitoring in Prince William Sound, 2002. Photo by John Whitney, NOAA.

This made the field collection of samples an ideal opportunity for a motivated and enlightened public to assist NOAA in implementing the program. In the later years of the monitoring, the field work was increasingly "crowdsourced" to residents of Prince William Sound, recreational boaters and charter vessel operators, and even other researchers who were working in the region on other projects. Future plans for the photo-monitoring now include the transfer of archival responsibilities to an Alaskan regional institution, which will substantially increase the availability and accessibility of the time series for those interested in environmental change—in the Prince William Sound region, in Alaska, and around the world.

Kasitsna Bay Rocky Intertidal Study, 1999-2013

During the first spill year of 1989, the cleanup on the shorelines of Prince William Sound continued in earnest throughout the summer. The oil, which had originally come ashore as a viscous liquid, changed as it weathered under exposure to the elements. As a rule, as oil weathers, it becomes increasingly more difficult to collect from the environment. In Alaska, oil that had coated the rocky intertidal and seeped into cracks and crevices thickened like a dark paint and no longer floated on the surface of the water on its own. As a result, responders turned to increasingly more aggressive means to mobilize the stranded oil. One of the favored approaches was the spraying of large volumes of high-pressure hot water to remove the oil from the rocky shoreline, and then contain and collect it. Large floating hot water delivery systems with names like Omni-Boom (modified articulated concrete delivery systems) and Maxi-Barge were built and deployed as the tactical centerpieces for cleanup teams.

As previously detailed, the original NOAA long-term monitoring program was designed to determine the impact of these more intrusive cleanup activities. While the larger questions of cleanup impacts relative to oil impacts were addressed in the program, more subtle questions about the drivers for change and trends in the intertidal zone remained.

Omni-Boom equipment (left) delivering high-pressure hot water for shoreline cleanup, 1989. Photo by Allan Fukuyama.

In 1999, to investigate these in a setting more controlled and structured than during a major oil spill response, NOAA initiated a rocky intertidal experiment in Kasitsna Bay, located across Kachemak Bay from Homer, AK. The study was designed to answer the questions: How long do rocky intertidal communities require for recovery from aggressive shoreline treatment? And, what are the characteristics of that recovery? Was the large degree of variability from year to year an artifact of oil spill impact, or did it characterize life in the intertidal zone of Prince William Sound?

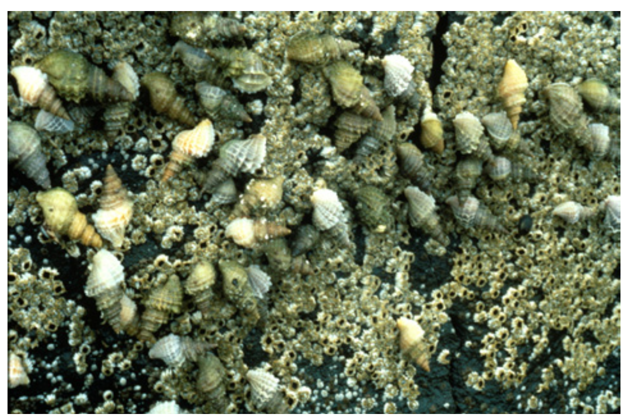
Although Lower Cook Inlet was an area at risk during the *Exxon Valdez* spill, oiling impacts in the Kachemak Bay system were modest, and no oil was reported in Kasitsna Bay. The physical and biological characteristics of the study site are similar to others throughout the Gulf of Alaska and to sites that were exposed to oil and were the focus of post-spill monitoring following the oil spill.

The study site was situated in the Herring Islands within Kasitsna Bay, which in turn is located within the Kachemak Bay National Estuarine Research Reserve. The site was composed of shallow sloping bedrock that supported a biological community similar to that found in Prince William Sound, dominated by mussels (*Mytilus trossulus*), barnacles, and rockweed (*Fucus distichus*, a common seaweed on Pacific shorelines). Common intertidal grazers included periwinkle snails (*Littorina* spp.) and limpets (*Lottia* spp.), while an important predator was the deceptively benign-looking snail or drill (*Nucella* sp.). Other voracious—but less photogenic—rocky intertidal predators included the nemertean worms (e.g., *Emplectonema* sp. and *Amphiporus* sp.).

Pacific blue mussels (*Mytilus trossulus*). Photo by Mandy Lindeberg, NOAA Fisheries, Auke Bay Laboratory.

Rockweed (*Fucus distichus*). Photo by Mandy Lindeberg, NOAA Fisheries, Auke Bay Laboratory.

Sitka periwinkle, *Littorina sitkana*, with egg mass. Photo by Gary Shigenaka, NOAA.



Feeding frenzy—the sound of a thousand barnacles screaming. Drills (*Nucella lamellosa*) preying on barnacles (*Balanus* and/or *Semibalanus* sp.). Photo by Gary Shigenaka, NOAA.

Along the west shore of the islet, 36 permanent plots (i.e., marked with stainless steel bolts) were established on bedrock at tidal heights of 1.3-3.3 (average tidal amplitude in this region is approximately 4.8 m). Plots spanned a distance of 61 m (east to west), were separated by a minimum distance of 25 cm, and were arranged in twelve blocks consisting of three plots each. Within each block of three, plots were randomly assigned to treatment and control groups (two treatments, one control).

Aerial view of the Kasitsna Bay study site. Photo by Terrie Klinger, University of Washington.

Field biologists establishing rocky intertidal study plots in Kasitsna Bay, AK, 1999. Photo by Allan Fukuyama.

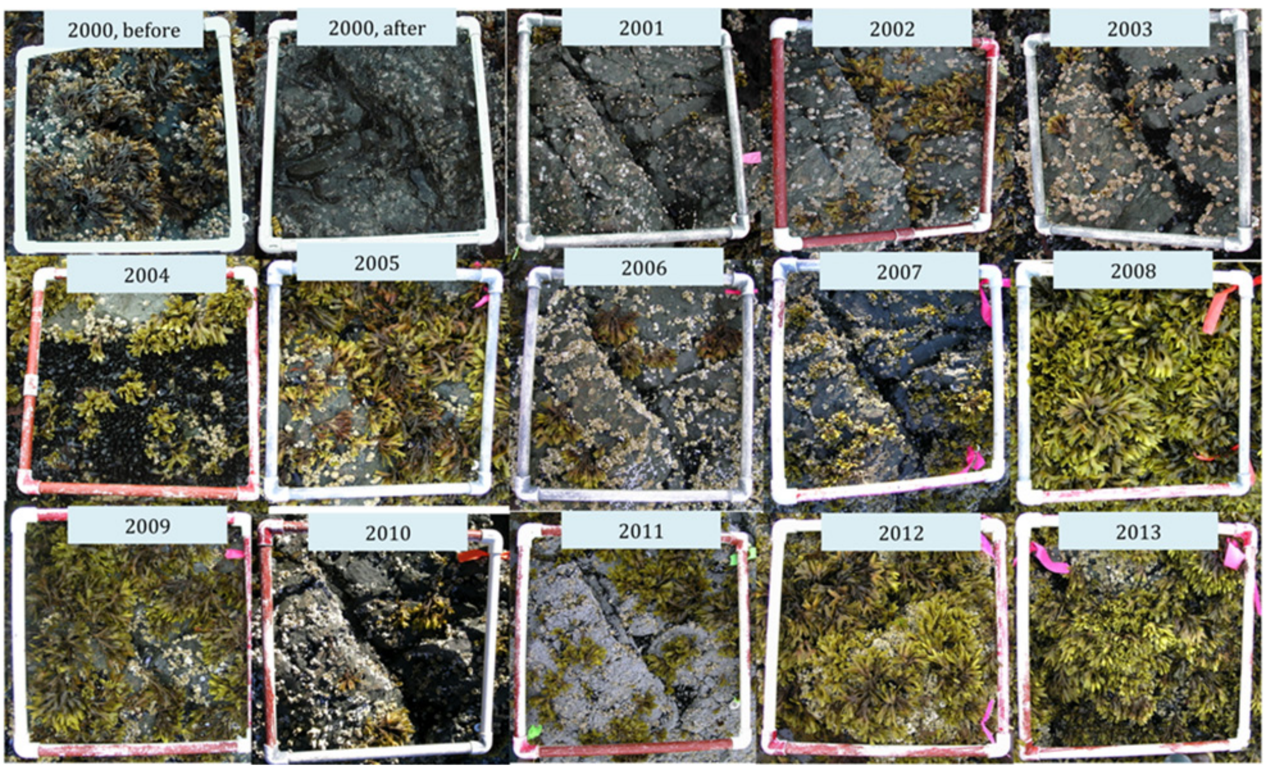
In treatment plots, an intense pulse disturbance was imposed by manually clearing 50 cm X 50 cm plots of all surface plants and animals, followed by surface sterilization using a hand-held propane torch. This simulated extremely aggressive shoreline cleanup impacts. One treatment plot in each block was cleared in July 1999. A second treatment plot in each block was cleared in July 2000 to test for inter-annual differences in response to disturbance. The third plot in each block was untreated and served as a control plot.

The strongest signals of disturbance were manifested in rockweed and mussels. Abundance of the rockweed was very low in the year immediately following clearing (not surprising given the intensity of the disturbance), but subsequently quickly recovered to levels of abundance observed in control plots within two years. Mussels showed sharp declines in abundance in the year following clearing, but in contrast to the rockweed, took several years to recover to levels of abundance observed in control plots. Barnacles, periwinkles, and limpets recovered quickly and returned to pre-disturbance levels within a year after clearing.

Field biologist sterilizing rocky intertidal study plot at Kasitsna Bay study site, 1999. Photo by Gary Shigenaka, NOAA.

Limpet (*Lottia scutum*). Note path of grazing. Photo by Mandy Lindeberg, NOAA Fisheries, Auke Bay Laboratory.

The rapidity with which most of the common shoreline species recovered from the severe treatment may have reflected the fact that disturbance is an integral feature of the intertidal zone, and that common survival strategies there accommodate it by producing large numbers of progeny, and opportunistically and constantly exploiting any open settlement substrate.

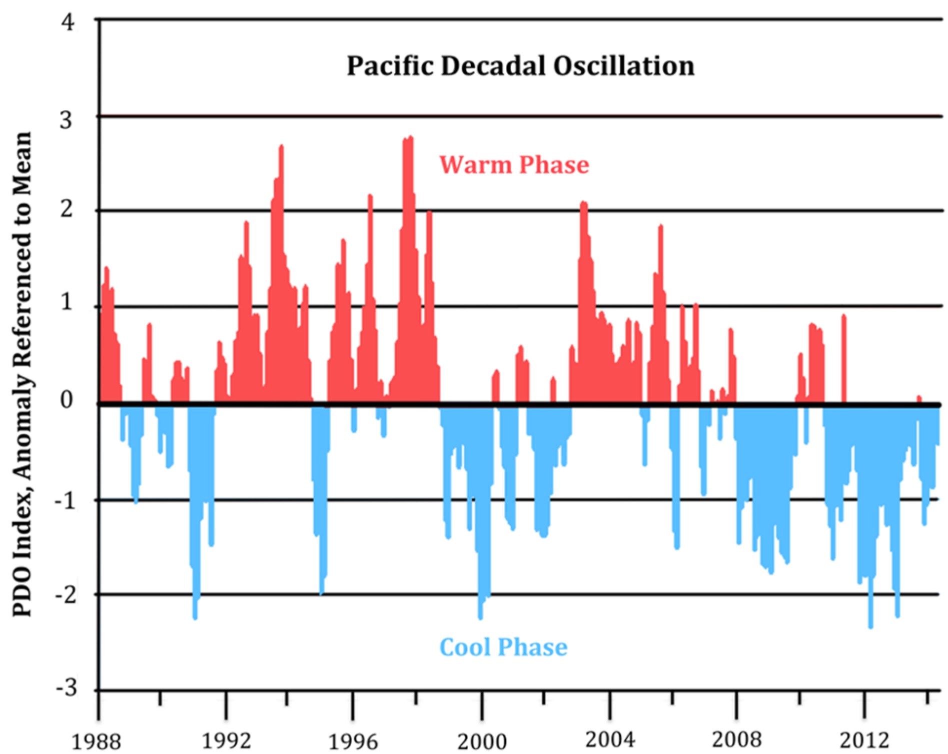


Time series of a treated plot in Kasitsna Bay, 2000-2013. The first photographs, upper left, show before and after clearance differences in 2000. Photo mosaic by Terrie Klinger, University of Washington.

The control plots in the Kasitsna Bay experiment showed a great deal of variability from year-to-year that was obviously not associated with the disturbance imposed on the other treated plots. Mean values of abundance were calculated over the entire 13-year study period, which provided a reference for comparing each individual year. Plots of the data configured in this way showed whether species abundances in any given year were greater or less than the long-term average.

These results showed temporal patterns of greater or lesser abundance that were distinct for each intertidal species: mussels occurred in greater numbers over certain periods of time, limpets and barnacles were similar in their cycles, while rockweed showed the opposite pattern for the same periods of time. This led to the inevitable question of: Why? What was driving these patterns?

Statistical comparison of the biology results with potential physical or climatic drivers yielded the surprising correlation between abundances of rocky intertidal species in the experimental study plots with a large-scale oceanic cycle: the Pacific Decadal Oscillation (PDO). This is a recently (1996) described phenomenon first defined in a University of Washington dissertation researching linkages between Pacific salmon and climate. The PDO is detected as warm or cool surface waters in the Pacific Ocean, north of 20° N. latitude. During a "warm", or "positive", phase, the western Pacific becomes cool and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs. As the "decadal oscillation" in the name implies, the pattern shifts phases on a long-term time scale.

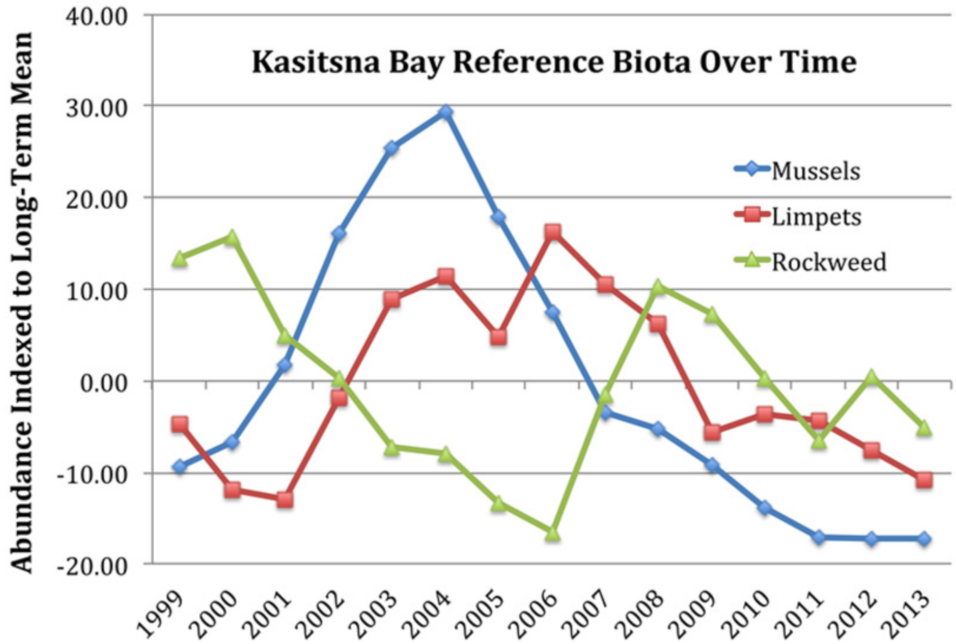


Variation in PDO since the *Exxon Valdez* oil spill. N. Mantua, University of Washington.

Researchers at the University of Washington Joint Institute for Study of the Atmosphere and Oceans have noted:

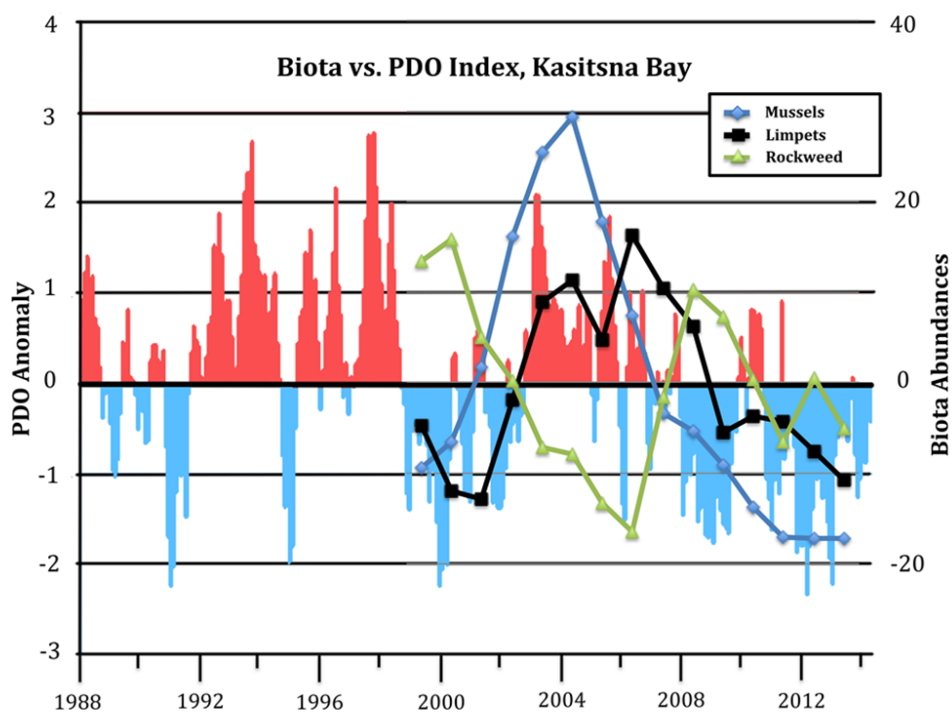
> "Major changes in northeast Pacific marine ecosystems have been correlated with phase changes in the PDO; warm eras have seen enhanced coastal ocean biological productivity in Alaska and inhibited productivity off the west coast of the contiguous United States, while cold PDO eras have seen the opposite north-south pattern of marine ecosystem productivity."

In the Kasitsna Bay experiment, we found that mussels occurred in "net positive" abundances (i.e., greater than the long-term mean) during the warm phase of the PDO, and showed negative anomalies during the cool phases of the PDO. Limpets showed a similar trend with respect to the PDO. Conversely, rockweed reflected the opposite response: it tended to be less abundant than the long-term average during the warm phase of the PDO and more abundant than the long-term average during cool phases of the PDO. The relationship of barnacle abundance to the PDO was less clear, although barnacles did appear to be more abundant than the long-term mean during the positive phase of the PDO, and less abundant during cool phases of the PDO.



Mussel and limpet abundances and rockweed cover at untreated control plots for the Kasitsna Bay experiment, 1999-2013. Referenced to long-term mean abundances/cover.

The association between abundances and PDO phase becomes clear if we plot them together, with time as the common denominator:



Indexed mussel and limpet abundances and rockweed cover at untreated control plots for the Kasitsna Bay experiment, 1999-2013, overlaid on PDO anomalies.

The major biotic constituents of the Alaskan rocky intertidal are certainly interconnected, directly or indirectly: through predator-prey or grazer-grazed relationships, one organism providing favorable substrate or protection from physical disturbance or predators, or effects of subtle chemical cues. We can speculate, but not state with much certainty, how a warm or cool phase of the PDO might invoke its salutary or inhibitory effect on a given organism. It might be a directly favorable effect; or it might inhibit a competitor or predator. Thus, a heavy crop of rockweed in the intertidal zone is likely the consequence of a complex interplay among grazer abundance, protective substrate availability, and a host of other factors we may have not considered or understood. The correlation to a factor like the PDO provides hints, but not the answers.

The Kasitsna Bay experiment reinforced the notion that the intertidal environment is a place that constantly changes, and over relatively short periods of time. If we impose an intense disturbance on rocky intertidal habitat, it reflects that impact—and then it responds, and immediately begins the process of compensation and recovery. It did not take a long time for disturbed study plots to recover to the point where they were comparable to undisturbed control plots. This is not to say that they returned to what they were before the disturbance, but rather, they returned to a condition typical for unimpacted areas at the same time.

In summary, the Kasitsna Bay study supported the following conclusions:

1. The system is dynamic. The major taxa (barnacles, mussels, rockweed) vary in abundance on short time scales (e.g., one to several years) and small spatial scales (e.g., meters to tens of meters).
2. The system is resilient. Although the abundance of taxa varies in time and space, the community itself has remained in the same state (or phase) over the 15-year period of sampling.
3. Interannual variation in community composition and in the abundance of key taxa appears to be associated with changes in the Pacific Decadal Oscillation.
4. Recovery from intense disturbance (clearing) is rapid for most taxa. Recovery of barnacles, limpets, and littorine snails occurred within one year; recovery of rockweed occurred within 2 years of disturbance; and recovery of mussels took about 5 years.
5. The data are consistent with the parallelism model of recovery, and (for most taxa) also consistent with a convergence model of recovery. The data do not support the return-to-predisturbance-conditions model.

The concept of a constantly changing baseline condition is a challenge for impact and recovery assessment now and in the future. Although the Kasitsna Bay study provides some reassurance that the rocky intertidal recovers quickly, it also suggests that the definitions of "recovery" and "restored" require understanding of variability and change for specific habitats of concern.

Lower Herring Bay Gravel Beach Study, 2000-2012

During the cleanup phase of the oil spill between 1989 and 1991, observers noted that washing operations on gravel beaches, in particular, frequently resulted in sediment plumes in the nearshore environment. The photograph on the next page shows an aerial view of one of the NOAA long-term monitoring sites at Block Island being treated in July 1989. A plume of fine-grained sediments is visible trailing away from the treatment zone to the left (north).

Because the animals that reside in the interstitial spaces of depositional sediments, called infauna, are known to prefer or require specific grain size characteristics, this led NOAA response scientists to suggest that alterations in the physical structure of gravel beaches in Prince William Sound treated during the *Exxon Valdez* response might delay the biological recovery process. Although sediment grain size was measured during the 1989-2000 long-term monitoring program, samples were not paired with biological collections and so direct comparisons could not be made.

NOAA Block Island study site, July 1989. Photo by Lewis Consiglieri, NOAA.

Experimental study site in Lower Herring Bay, July 2000. Photo by David Janka, *Auklet* Charter Services.

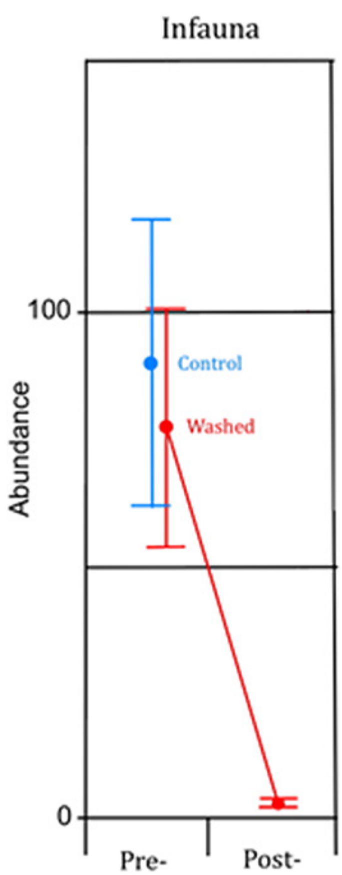
In 2000, an experiment was established in Lower Herring Bay, on the western side of Knight Island in Prince William Sound, to specifically focus on this potential linkage and address the question: does aggressive cleanup change the physical structure of gravel beaches to the extent that biological recovery is delayed?

According to treatment records from the spill response, Lower Herring Bay did not receive much oil in 1989 and little, if any, substantive cleanup activity took place there. The shoreline, therefore, would represent a reasonable surrogate for pre-spill, pre-treatment conditions. A long (approximately 200 m) sheltered gravel study beach was selected along the southern shore of the embayment, and twelve paired 3 m X 3 m plots were designated at the 1 m tidal elevation. In each paired plot, treatment/no treatment status was randomly assigned. Those plots designated for treatment were manually excavated down to 25-50 cm, placed in 10 mm mesh sieve trays, and washed to remove both fine-grained sediments and infauna. The treatment was chosen to simulate a very aggressive washing operation on the beach. The other plot in each pair was left intact. Infauna and grain size samples were collected at each plot before and after the washing treatment.

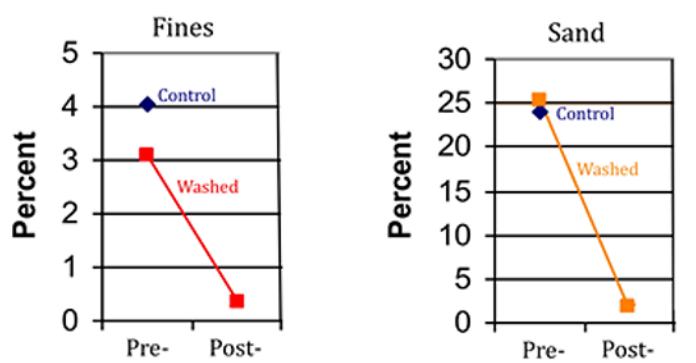
Most abundant mollusks found at the Lower Herring Bay site: from top to bottom, *Cingula* sp.; *Alvania compacta*; the unfortunately named *Fartulum occidentale*; and *Rochefortia tumida*. Photo by Jeff Cordell, University of Washington.

Grain size measurements and infaunal analysis showed that the washing, as would be expected, substantially changed both the physical and biological conditions: percentage of finer-grained sediments (< 2 mm) was drastically reduced; and most infauna were washed out. These changes are showed in the graphs below.

Washing fine-grained sediments from Lower Herring Bay study plots, July 2000. Photo by Gary Shigenaka, NOAA.



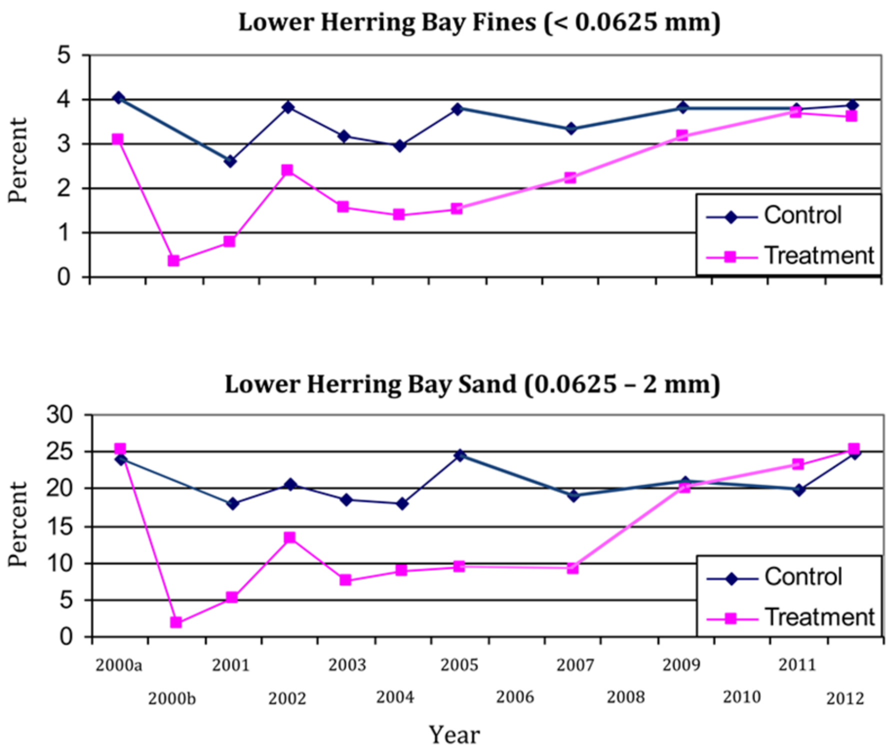
Reduction in infaunal abundance in treated study plots (red) from washing through 10 cm sieves in July 2000. Untreated (control) abundance shown in blue.



Reduction in fine-grained sediments (fines, <62.5 µ; and sand, 62.5 µ-2 mm) in treated study plots (red & orange) from washing through 10 cm sieves in July 2000. Untreated (control) values shown in blue.

In the years between 2000 and 2012, the Lower Herring Bay site was revisited annually[4] and all plots were sampled for grain size structure and infauna. The trends over that period of time in part met our expectations, but also surprised us—such is the nature (and value) of longer-term research.

The results indicated that grain size structure, and the finer-grain component of the washed beach sediments, took a long time to recover to comparability with the unwashed controls. That is, after we washed out most of the sediments measuring less than 2 mm, the grain size structure did not match that at the unwashed control plots until the final year of field sampling, in 2012. The figures below show the percent fines and percent sand was relatively constant at the control plots at 3-4 percent, and 20-25 percent, respectively. Percentages of both sediment classes steadily converged toward the control values until 2012, when there was no difference between treated and controls.



Trends in grain size at Lower Herring Bay experimental site, showing re-establishment of finer grained material over time. 2000a and 2000b show the effective removal of sands and fines by the washing process.

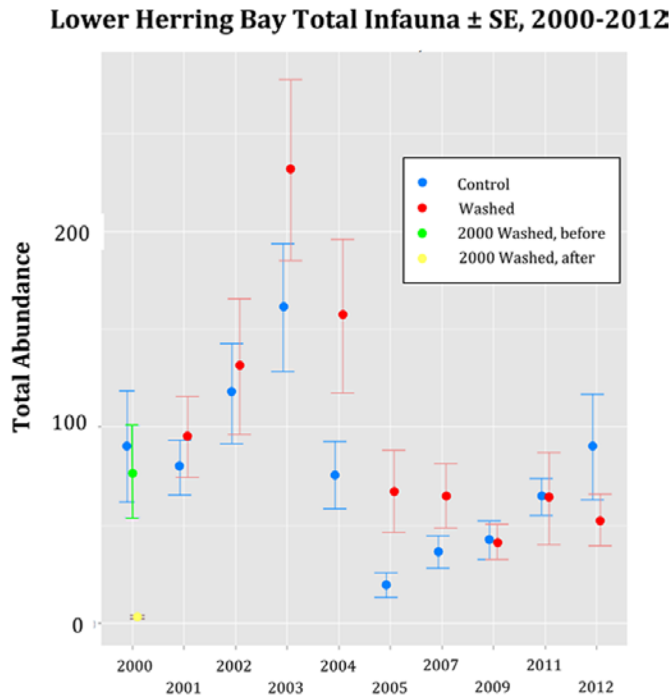
This slow recovery of fine grains makes some intuitive sense, as sources of smaller size fractions are glacial fines and materials carried by streams entering Prince William Sound.

The biology results were more surprising. Despite the long-term disruption of grain size structure in washed plots and the effective elimination of the resident infaunal communities, those infauna recovered quickly—at least in terms of the gross metric of total infaunal abundance, which showed no significant differences between washed and unwashed after only one year. In years three and four post-disturbance, abundances at the washed sites actually exceeded those at the control sites, possibly reflecting a compensatory process.

[4] With the exception of 2010, when another oil spill occurred in the Gulf of Mexico.

Infaunal core sampling at Lower Herring Bay, 2007. Photo by Allan Fukuyama.

Even the more nuanced variables of diversity and richness of the biological communities showed a similar trend of apparent recovery: by 2003, indices of diversity and species richness at washed and unwashed plots were virtually the same.



Total infaunal abundance at Lower Herring Bay experimental site, 2000-2012. Green and yellow show before and after infaunal measurements for washing in 2000.

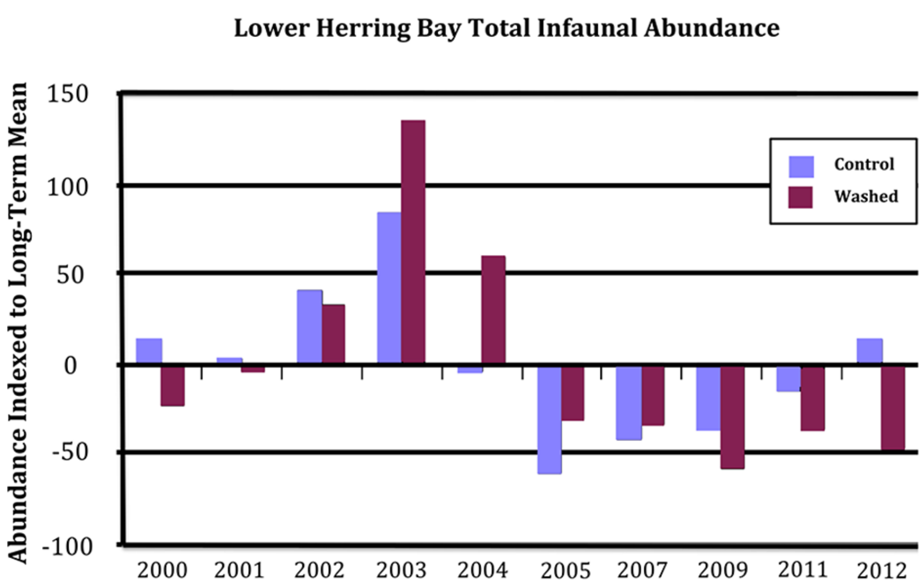
Shannon diversity and species richness at Lower Herring Bay control and treatment plots 2000-2012; n=12 each year and plot type.

Year	Plot Type	Shannon Diversity	Species Richness
2000	Control	1.52	10.67
2000 Pre-treatment	Treatment	1.53	9.08
2000 Post-treatment	Treatment	0.58	2.11
2001	Control	1.80	11.67
2001	Treatment	1.52	10.75
2002	Control	1.61	10.92
2002	Treatment	1.50	10.17
2003	Control	1.56	13.17
2003	Treatment	1.50	12.58
2004	Control	1.34	8.50
2004	Treatment	1.44	9.92
2005	Control	1.10	4.36
2005	Treatment	1.06	5.58
2007	Control	1.40	6.75
2007	Treatment	1.10	7.00
2009	Control	1.43	8.33
2009	Treatment	1.48	7.83
2011	Control	1.65	9.50
2011	Treatment	1.49	7.50
2012	Control	1.43	8.75
2012	Treatment	1.47	8.42

Although we are careful not to extrapolate the results from a single study at one location too broadly, we can say that biological recovery of the infauna residing in a highly disturbed and modified beach occurred over a much shorter time frame than did the physical recovery of beach structure. We can speculate reasons for this apparent disconnect; it may be related to the overall lack of fine-grained sediments in the Prince William Sound system. With the shorelines largely comprised of rocky, gravel, and boulder-cobble beaches and flats, infauna requiring finer-grained material may simply not be present as an important part of the biological community. Gravel-adapted communities would respond quickly to available habitat, especially since the acutely toxic component of an actual oil spill—the oil itself—was not part of the experiment.

Field sieving Lower Herring Bay infaunal core samples, 2011. Photo by Gerry Sanger, Sound Ecosystem Adventures.

The Lower Herring Bay experiment satisfied our primary objectives of learning how a gravel shoreline in Prince William Sound physically and biologically responds to a known, intensive, and pulsed disturbance. Like the other experiments we have discussed, the longer-term duration of the Lower Herring Bay study also permitted us to examine the nature of background or natural variability that we observed over the course of the experiment. The results from the control plots as well as the biologically recovered plots appeared to reflect a consistent but variable response to conditions from year-to-year. Referencing the results to long-term means provides an additional perspective for portraying this response.



Total infaunal abundance at Lower Herring Bay, 2000-2012, showing similarity in temporal trends between control and washed plots post-recovery from disturbance.

As with the NOAA monitoring and other experimental work, these results from Lower Herring Bay support the idea that environmental recovery is both convergence toward, and synchrony with, a dynamic reference point that is constantly shifting. Before we can answer the question, "Is it recovered?" it is necessary to understand where we have been and the likely drivers for where we are going.

Littleneck Clam Studies, 1991-2007

The native littleneck clam, *Leukoma staminea* (recently renamed by bored taxonomists from *Protothaca staminea*), is a common inhabitant of the lower intertidal zone on well-sheltered Pacific coast beaches and estuaries with a component of mud or sand. It ranges from Baja, California, to the Aleutian Islands in Alaska. Its wide geographic distribution and relative accessibility in the intertidal zone made *Leukoma staminea* an important commercial and recreational shellfish species along the Pacific coast, although more recently, non-native shellfish have become favored by commercial harvesters. In Prince William Sound, native littleneck clams are encountered on gravel beaches, and the clam is a regular part of the subsistence diet for native villagers in the region. Littleneck clams are also important prey items for wildlife like sea otters, shorebirds, and sea stars.

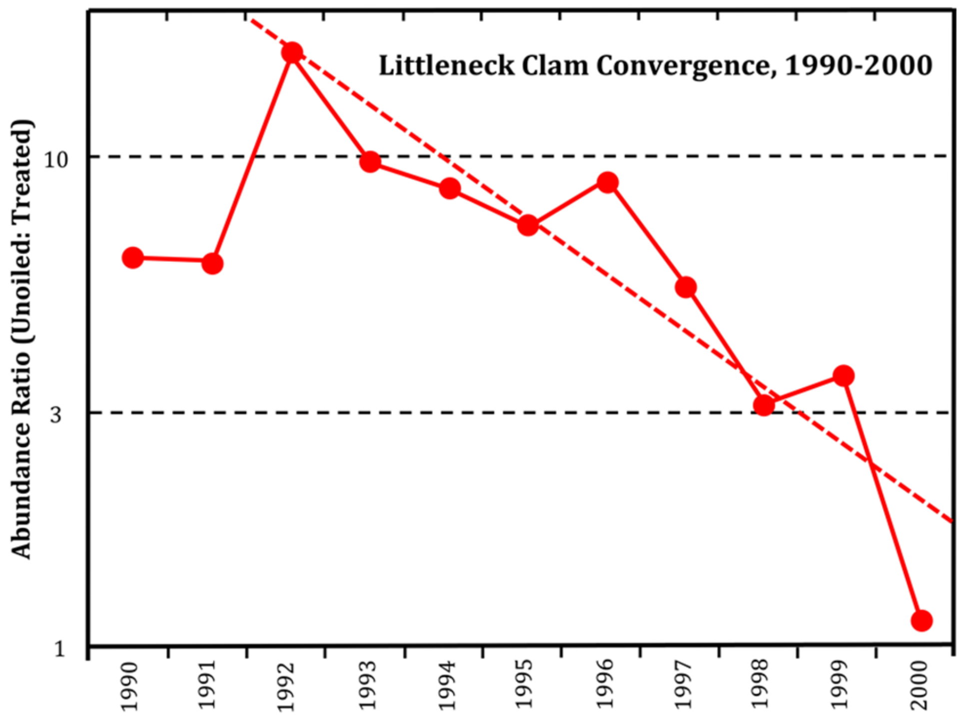
Native littleneck clams, *Leukoma staminea*, collected at Hogg Bay, July 1999. Photo by Gary Shigenaka, NOAA.

The *Exxon Valdez* oil spill affected many beaches with resident populations of littleneck clams. Because of its widespread occurrence, importance to human and wildlife consumers, and close association with potentially contaminated beach habitat, the native littleneck clam was added to the NOAA Long-Term Monitoring Program as a targeted species in 1991.

Impacts of the *Exxon Valdez* oil spill were most pronounced in the middle to upper intertidal portions of Prince William Sound beaches, as this was where the oil tended to strand and where shoreline cleanup was concentrated. Littleneck clams—generally residing lower in the intertidal and under the surface of the beach substrate—would be sheltered, to some extent, from the extreme conditions of oil exposure and intrusive cleanup techniques. Nevertheless, acute impacts of "dead or moribund" littleneck clams were noted anecdotally during the first year of the spill, littering the surface of an oiled and untreated beach in Northwest Bay. After washing, more dead clams were observed and measured densities of live clams were low. Surface disruption of the beach buried clams under deep layers of washed sediments.

Between 1990 and 1993, the NOAA Long-Term Monitoring Program documented a pattern of recovery for a number of intertidal biota that we termed "parallelism." That is, within one to two years of the spill, numbers of taxa, and other cumulative species parameters such as total cover, exhibited dramatic increases at impacted sites relative to controls. Following the repopulation event, changes occurring at oiled sites generally tracked those at the unoiled reference sites.

Interestingly, the temporal trend for native littleneck clams did not reflect the typical parallelism template. Specifically, *Leukoma staminea* did not show the immediate depression in numbers followed by a burst of recruitment at impacted sites in the first few years, and also did not reflect the initially non-parallel abundance trend with reference sites. In fact, clams at the oiled and washed sites showed remarkably similar patterns of abundance to clams at unoiled reference sites from the beginning of the monitoring effort. A closer examination of the results, however, suggested that the native littleneck clam populations at the impacted sites may have shown a slow and subtle recovery in absolute abundance. Specifically, abundances for unoiled sites and for oiled and washed sites steadily converged from 1992 through 2000. When the long-term monitoring came to a close in 2000, it appeared that the two populations had indeed converged to another state of apparent recovery.



Convergence (recovery of clam abundances at washed sites referenced to control sites). Ratio of abundance at unoiled sites to oiled & treated sites; a value of 1 means that abundances are equal. Dotted red line is linear regression line.

In 2007, the NOAA research team was funded by the *Exxon Valdez* Oil Spill Trustee Council to revisit the recovery status of littleneck clams at the Prince William Sound monitoring sites. The expectation for the survey had been the confirmation of the apparent recovery noted in 2000, with possibly additional insights into the stabilization of recovered populations.

However…the native littleneck clams in Prince William Sound proved to be uncooperative, and completely confounded the recovery assessment. In fact, the 2007 NOAA survey resulted in a number of new questions that extended beyond long-term oil spill assessment and far beyond Prince William Sound. That is: the 2007 field work revealed that **abundances of littleneck clams had unexpectedly declined, relative to the 1990-2000 period, across Prince William Sound, regardless of oiling history**. The extent of the decreases was significant, around an order of magnitude from previously documented population levels at surveyed sites. Totals from the 2007 survey are shown in the following table.

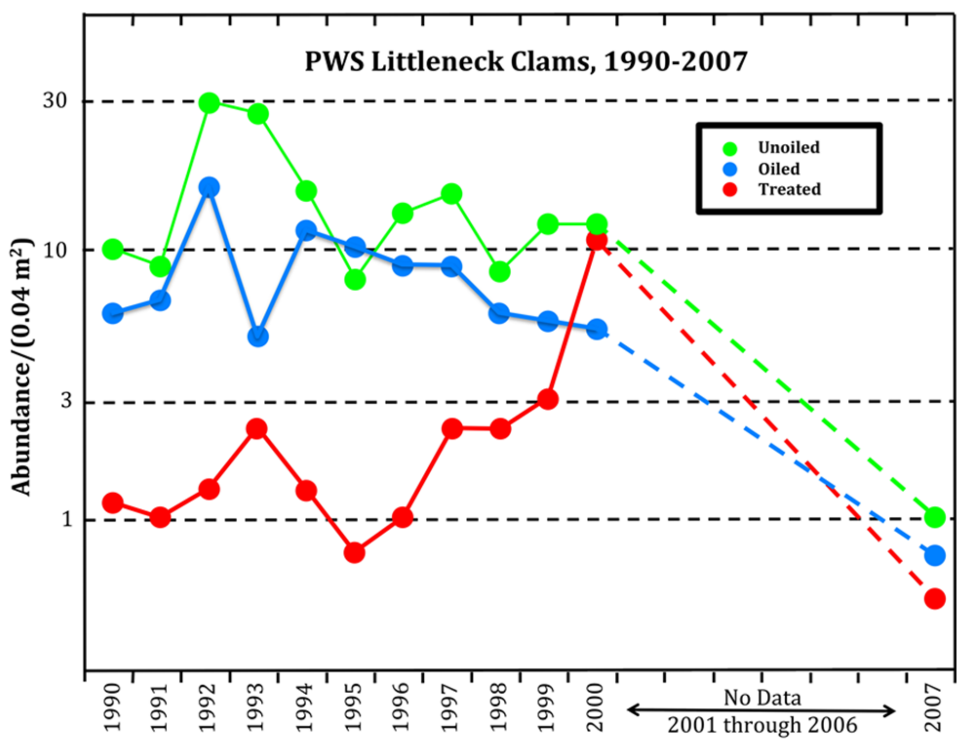
Densities per m^2 of *Leukoma staminea* clams encountered in excavations in Prince William Sound for sampled years, 1991-2007.

	1991	1992	1994	1999	2007
UNOILED	271	355	440	231	14
OILED/UNWASHED	283	656	685	145	31
OILED/WASHED	10	22	41	89	4

UNOILED	1991	1992	1994	1999	2007
Bainbridge	N/A	N/A	N/A	N/A	0.7
Crab Bay	N/A	62	69	55	N/A
Outside Bay	94	58	33	74	0
Sheep Bay	177	235	338	102	13.3

OILED/UNWASHED	1991	1992	1994	1999	2007
Block Island	112	420	337	N/A	18.7
Snug Harbor	46	45	58	30	2
Mussel Beach	95	176	263	31	10
Herring Bay	30	15	27	97	0.4

OILED/WASHED	1991	1992	1994	1999	2007
Sleepy Bay	0	2	N/A	N/A	0.7
Shelter Bay	10	10	N/A	43	0
NW Bay W. Arm	0	10	41	48	3.3



Native littleneck clam abundance at NOAA monitoring sites, 1990-2007.

Communications with state and provincial shellfish resource managers along the Pacific coast of North America indicated that similar trends of decline had been observed in other widely-separated portions of the coast, including British Columbia and northern Puget Sound. Some—but not all—recreational harvest beaches in Kachemak Bay, AK, also showed steep declines around the same time period.

More recent field surveys in 2010 confirmed declines in Prince William Sound clam abundances, most pronounced for littleneck clams. A definitive cause of these bivalve declines has not been identified at this writing; however, potential contributing factors have been discussed in reports and the literature as including ocean acidification, disease organisms, and phytoplankton declines. We do not have the answer for the question, what caused the significant declines in widely distributed populations of a clam that we consider to be an important intertidal organism?

We can, however, note the effect that this decline—clearly unrelated to oil or cleanup impacts—had on our ability to ascertain recovery in an impacted system. What had been a study that was poised to provide empirical information on the course of recovery after a major oil spill was completely pre-empted by an overwhelming influence that affected target species abundances across the region. This is the cautionary tale for future oil spill assessment, especially in the Arctic: there are larger forces at work, with amplitudes of change that can complicate or obfuscate past reliable approaches to environmental assessment. How do we plan for these situations?

The "So What?" Question

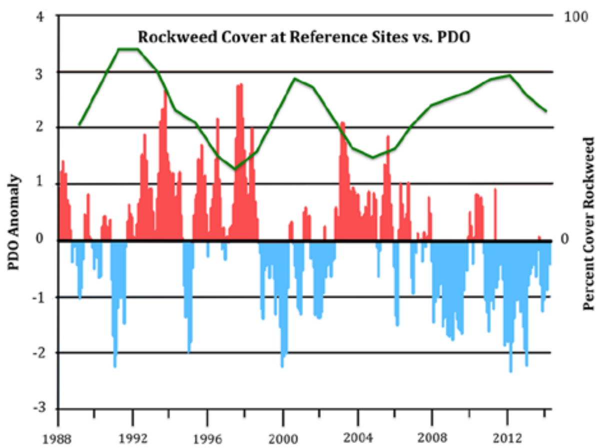
From the very beginnings of NOAA's oil spill response activities in the 1970s, the core underlying focus has been the application of science to supporting operational and tactical efforts to mediate spill impacts. Where will the oil go? How will shorelines be affected? What are the most effective cleanup methods? When is cleanup doing more harm than good? How clean is clean? What is a good way to measure recovery?

NOAA's spill science has always focused on applying the answers to "so what?" questions for improving oil spill response support. For the *Exxon Valdez*, all of the activities we have described here—from the on-scene scientific support, short- and long-term monitoring, and experimental work—were designed to provide information that would guide ongoing cleanup activities or to answer defined questions concerning the effects of cleanup. Lengthier studies, like the NOAA Long-Term Monitoring Program or the experimental studies initiated afterward, have provided additional more subtle, and perhaps more provocative, insights that are relevant to the assessment of future spills and disturbances, particularly with respect to the consideration of environmental variability as a confounding and sometimes predominant element.

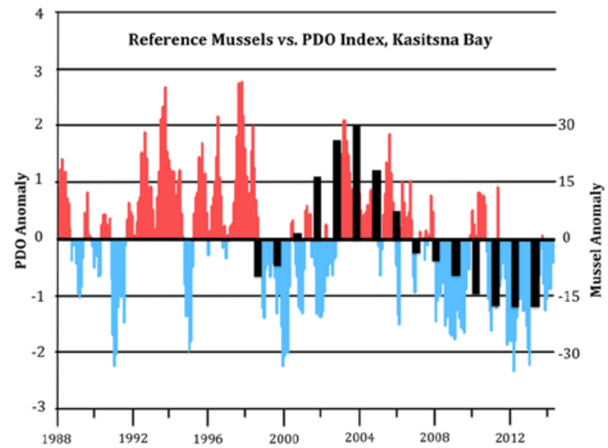
In addition to the impact and recovery from acute stressors, the year-to-year and longer-term variability in intertidal populations was a consistent hallmark of all of the NOAA experimental studies. Each of the three long-term experiments (Mearns Rock, Kasitsna Bay, and Lower Herring Bay) included measurements of abundances or percent cover of key intertidal organisms in plots or sites unaffected by oil and cleanup. As part of the exploratory analysis, patterns of biological variability were compared with indices of changing ocean conditions.

The results across the three independent experimental studies contained a surprising common thread: despite high year-to-year variability, there is a strong correlation of qualitatively different biological metrics with cycles of the Pacific Decadal Oscillation (PDO). Previous studies along the Pacific coast had correlated intertidal biological conditions with physical oceanographic processes such as currents and upwelling, but the findings from the NOAA experimental spill studies in discrete locations across 300 km in Prince William Sound and Cook Inlet are among the first to link biological communities with large-scale temporal oceanic cycles. Four figures below, from the three different experiments, show results of biological assessments plotted against the PDO index values for the same periods of time.

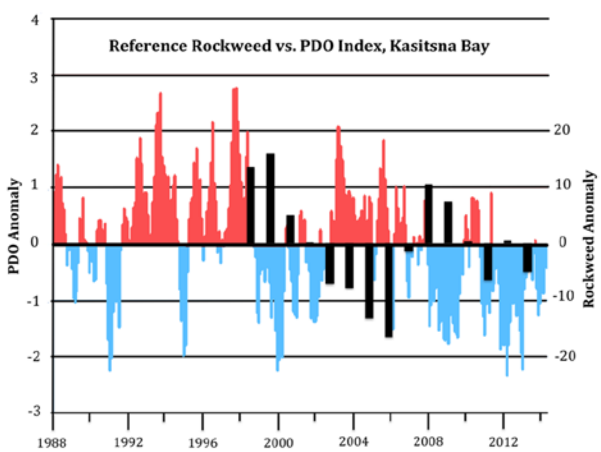
The plots reflect that mussels and mollusks as a group appear to respond positively/favorably to warmer cycles of the PDO. Two analyses of rockweed show the inverse pattern of greater abundance during cool phases.



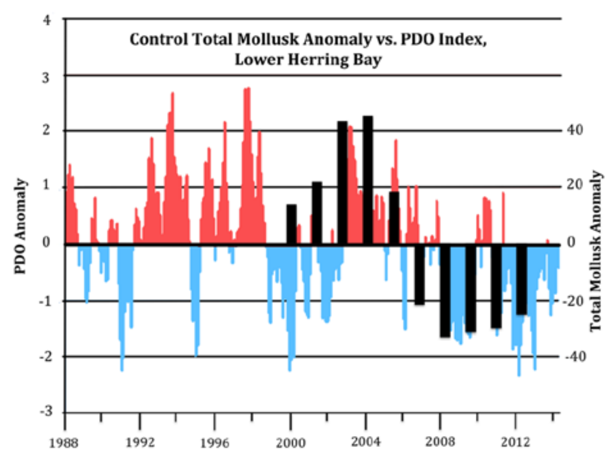
Three-year moving average cover of rockweed (green line, estimated from photographs) at Prince William Sound reference sites, 1989-2013, suggesting association with cool phase of PDO index.



Indexed (to long-term mean) mussel abundance at Kasitsna Bay reference sites (black bars), 1999-2013, plotted against long-term PDO index. Note correlation with warm phase of PDO index.



Indexed (to long-term mean) rockweed cover at Kasitsna Bay reference sites (black bars), 1999-2013, plotted against long-term PDO index. Note correlation with cool phase of PDO index.



Indexed (to long-term mean) total molluscan abundance from Lower Herring Bay reference sites (black bars), 2000-2012, plotted against long-term PDO index. Note correlation with warm phase of PDO index.

These patterns and correlations are interesting…but *so what*? That is, are they of any consequence or applicability in the context of understanding oil spill impacts and recovery?

It is a cliché to say that we live in a changing world; yet nowhere is the statement more empirically evident and with widespread implications than in Arctic and subarctic regions like Alaska. Changes in Arctic biological communities like the sea pigeon (black guillemot, *Cepphus grille mandti*) were among the first to be correlated to seemingly distant and unrelated large-scale environmental trends measured at Mauna Loa (where changes in atmospheric carbon dioxide have been measured since 1958) or in the deep waters of the Pacific (where carbon dioxide equivalents and acidic conditions have been increasing steadily).

In recent years, the linkages between changes in Alaskan communities and conditions, and the portfolio of large-scale atmospheric, oceanic, and climatic shifts have grown more numerous—and mostly, worrisome. The prospect of an ice-free Arctic that until recently seemed unthinkable as a near-term possibility is now viewed as a virtual certainty within decades. A consequence of the warming Arctic is that the potential of offshore oil development and the use of the Arctic Ocean as a viable transportation corridor no longer are pipe dreams—they are part of the "new normal" and part of international and corporate strategic planning.

Chukchi Sea, September 2013. Photo by Zach Winters-Staszak, Genwest Systems, Inc.

An unavoidable fact of our new and rapidly changing Arctic environment is that the potential risk of oil spills, from new production and from multipurpose vessel traffic, is increasing and will continue to do so at an increasing rate. However, our abilities to respond and deal with oil spills in what remains an exceedingly challenging physical and logistical environment remain mostly unchanged—that is, low.

If the *Exxon Valdez* experience has taught us anything, it has emphasized the importance of variability as both a key feature of biological communities and a critical consideration to integrate into assessments of disturbance and recovery. As we inevitably consider oil spill scenarios for the Arctic, they are framed against the background of change that is occurring at unprecedented rates.

With these considerations in mind, what are the implications of *Exxon Valdez* findings that might be applied to potential spill assessments in the Arctic and elsewhere?

- Shorter-term (1-5 year) and longer-term (5-20 year) NOAA spill studies suggest that biological recovery from intensive shoreline disturbance is rapid—on the order of 1-2 years. The addition of oil, through toxicity effects, and possibly prolonged secondary disturbance impacts resulting from cleanup activities, double intertidal recovery time to roughly 2-4 years.
- "Set-aside sites," or oiled sites that have been designated as "no treatment" zones, are critical considerations for distinguishing the effects of oil from the effects of cleanup. Set-aside sites were essential components of NOAA short- and long-term monitoring during *Exxon Valdez* and have proven their value in monitoring the *Deepwater Horizon* oil and response impacts. They can be challenging to advocate and support in the cleanup-focused response, but should not be ruled out *a priori*.
- Variability is a given in assessing oil spill impacts. Characterization of that variability for conditions and biological communities of concern would best be undertaken now, before significant amounts of oil production and increases in commercial vessel traffic have occurred—keeping in mind that rates of change, in addition to the reality of change itself, will not remain constant.
- After the fact—i.e., after a spill has occurred—design of monitoring programs should acknowledge the importance of variability and quantification of variability by (somewhat counterintuitively) ensuring that a sufficient number of nonimpacted reference sites are sampled, in addition to the expected impacted sites.
- If pre-spill characterization of variability is not possible or available, post-spill assessments can accommodate/acknowledge inherent pre-existing differences in conditions at impacted and unimpacted sites, as well as physical or biological changes driven by large-scale drivers, by considering an approach like the parallelism framework, which incorporates both.

- Variability can be documented and conveyed in a range of ways, including simple photographs. Complexity of the field assessment and subsequent analysis depends on the intended use of the results.
- Environmental variability, even at the shoreline monitoring site level, appears to be at least measurably influenced by large-scale oceanic cycles like the Pacific Decadal Oscillation. The practical implication of this linkage would factor the stage of PDO into determination of reference or baseline conditions against which both impact and recovery might be measured.
- *Exxon Valdez*-derived experiments suggest positive associations of important intertidal organisms with warm phases of the PDO. That is, organisms like mollusks tend to be more abundant, rockweed cover less abundant. Recognition of PDO phase at the time of an oil spill or other disturbance may provide important context for determining current status and predicting future trends. However, impact assessment for a disturbance co-occurring with, for example, a PDO phase shift could be complicated by potentially associated changes.
- Monitoring of littleneck clam recovery showed that assessment of impact and recovery trends can be, at a minimum, complicated; at worst, stymied; by large-scale mechanisms with no known links to oil spills.
- Other studies and programs have shown that long-term trends of warming are evident not only for the Arctic, but also for the Bering Sea. Areas with intertidal zones shaped by cold water and ice-scour that become warmer and ice-free will change quickly and substantially and will be very difficult to assess in the context of disturbance effects and recovery.
- Gravel beaches—common in other parts of Alaska, and predominant in the Arctic—are some of the most difficult to treat after an oil spill. Ferocious weather conditions aside, oiled Arctic gravel beaches may be more problematic than those from the *Exxon Valdez* experience because an essential component that can reduce oil persistence—wave energy—is less prevalent in the Arctic.

As the above list suggests, we have learned much in the 25 years since the *Exxon Valdez* oil spill. However, we cannot end without noting one of the most important lessons: the value of long-term monitoring itself. Or to put it another way—the longer you look at something, the more you learn. In the case of the *Exxon Valdez* spill, after two years we understood that aggressive shoreline treatment caused more harm than the oil itself; after three to four years, we saw those differences diminish as biological productivity at the most impacted places compensated; after four to six years, shoreline communities had mostly recovered from spill activities; and over five to ten years, we discerned that changes occurring on the shoreline appeared to be linked to subtle, much larger-scale processes that we would not have noted had we not had the long-term record.

In 1996, a writer for *Scientific American* accompanied our field team to Prince William Sound. She noted the documentation at different scales by different means and different people, and compared it to what the French refer to as *mise-en-abîme*: windows within windows within windows, to infinity. Applying this metaphor to 25 years of *Exxon Valdez* monitoring and research, the smallest windows are important, because they are the science of what is being observed at the study site. But the larger windows are the context, the "so-what?" considerations that tell us why we should care about any of it. Long-term monitoring provides us with more and larger windows.

The challenge for the future—our challenge, our future—is that regions like Alaska, like the Arctic, at risk from new oil production and increased transportation activities, are also located at the leading edge of swift and significant environmental change. What is baseline? How do we quantify impact? What is recovery relative to a dynamic reference point? Is there biological or physical information that could be collected to aid in interpreting conditions during a future spill? The questions have not changed much since the *Exxon Valdez*; the answers, however, have become more complex, nuanced, and perhaps—urgent.

A Postscript: The Twisted Fate of the Ship

The last days of the *Exxon Valdez*: in the San Diego shipyard before the first name change. Photo from the collection of Gary Shigenaka, NOAA.

A popular myth exists that it is bad luck to rename a boat. It is unclear whether there is a size limit associated with the renaming prohibition, but it is possible that the ship originally known as the *Exxon Valdez* might be used to argue that it is indeed universally true.

When the *Exxon Valdez* was delivered to Exxon on December 11, 1986, it was the largest vessel ever built on the west coast of the U.S. On July 30, 1989, the crippled *Exxon Valdez* entered dry dock at National Steel and Shipbuilding in San Diego—its original birthplace. The trip south from Prince William Sound had not been without incident, as divers discovered hull plates hanging from the frame 70 feet below the surface that had to be cut away, and a ten-mile slick trailing behind the ship for a time prevented it from entering San Diego Bay.

Nearly a year and $30 million later, the ship emerged for sea trials as the *Exxon Mediterranean*. The *Exxon Valdez* had suffered the ignominy—and corporate hardship—of effectively being singled out in U.S. legislation (the Oil Pollution Act of 1990, OPA90) and banned from a specific U.S. body of water:

> SEC. 5007. LIMITATION.
>
> Notwithstanding any other law, tank vessels that have spilled more than 1,000,000 gallons of oil into the marine environment after March 22, 1989, are prohibited from operating on the navigable waters of Prince William Sound, Alaska.
>
> (33 U.S.C. § 2737)

With this banishment institutionalized in U.S. law, Exxon Shipping Company shifted the operational area for the ship to the Mediterranean and the Middle East and renamed it accordingly. In 1993, Exxon spun off its shipping arm to a subsidiary, Sea River Maritime, Inc., and the *Exxon Mediterranean* became the *Sea River Mediterranean*. This was shortened to *S/R Mediterranean*.

In 2002, the ship was re-assigned to Asian routes and then temporarily mothballed in an undisclosed location.


Exxon Mediterranean in Trieste, Italy, July 1991. Photo by Arki Wagner, used with permission.

Exxon filed suit in federal court challenging the provisions of OPA90 that had banned its tanker from the Prince William Sound trade route. In November 2002, the Ninth Circuit Court of Appeals upheld the Oil Pollution Act and its vessel prohibition provision (the Justice Department noting that to that time, 18 vessels had been prevented from entering Prince William Sound). While Sea River had argued that the law unfairly singled out and punished its tanker, and that there was no reason to believe that a tanker guilty of spilling in the past would spill in the future, the three-judge panel disagreed unanimously.

On October 21, 2003, single-hulled tankers carrying heavy oils were banned by the European Union. A complete ban on single-hulled tankers was to be phased in on an accelerated schedule in 2005 and 2010. There remains pressure to eliminate single-hulled tankers from the oil trade worldwide, so their days are clearly numbered.

In 2005, the *S/R Mediterranean* was reflagged under the Marshall Islands after having remained a U.S.-flagged ship for 20 years (reportedly in the hopes that it eventually would have been permitted to re-enter the Alaska-U.S. West Coast-Panama route for which it had been designed). The ship's name became simply *Mediterranean*.

In 2008, ExxonMobil and its infamous tanker finally parted ways when Sea River sold the *Mediterranean* to a Hong Kong-based shipping company, Hong Kong Bloom Shipping Co., Ltd. The ship was once again renamed, to *Dong Fang Ocean*, and reflagged under Panamanian registry. Its days as a tanker also came to an end, as the *Dong Fang Ocean* was converted into a bulk ore carrier at Guangzhou CSSC-Oceanline-GWS Marine Engineering Co., Ltd., China.

The *Dong Fang Ocean* labored in relative anonymity in its new incarnation until November 29, 2010. On that day, it collided with another bulk carrier, the *Aali* in the Yellow Sea off Chengshan, China. Both vessels were severely damaged; the *Dong Fang Ocean* lost both anchors, and the *Aali* sustained damage to its ballast tanks. The *Dong Fang Ocean* moved to the port of Longyan with assistance by tugs.

Disemboweling the beast: dismantling the oil transfer pipes aboard the *Mediterranean/Dong Fang Ocean* in Guangzhou, China, June 2008. Photo by Mike Wells, *Horizon Enterprise*.

With this last misfortune, the final countdown to oblivion began in earnest for the vessel-formerly-known-as-*Exxon-Valdez*. In March 2011, the ship was sold for scrap to a U.S.-based company called Global Marketing Systems (GMS). GMS in turn re-sold it to the Chinese-owned Best Oasis, Ltd., for $16 million. Intending to bring the *Oriental Nicety*, as it had been renamed yet one last time, ashore at the infamous shipbreaking beaches of Alang, Gujarat, India, Best Oasis was blocked by a petition filed by Delhi-based ToxicsWatch Alliance with the Indian Supreme Court on the grounds that the ship could be contaminated with asbestos and PCBs. ToxicsWatch Alliance invoked the Basel Convention, which restricts the transboundary movements of hazardous wastes for disposal. However, an environmental audit required by the court showed no significant contamination, and in July 2012, the *Oriental Nicety* was cleared to be brought ashore for its final disposition. The ship was reportedly beached on August 2, 2012.

Cargo transfer pipes departing the *Mediterranean/Dong Fang Ocean*, June 2008. Photo by Mike Wells, *Horizon Enterprise*.

Shanta Barley, writing for *Nature*, penned a wry obituary as a lead-in to her article about the last days of the ship:

> The *Oriental Nicety* (née *Exxon Valdez*), born in 1986 in San Diego, California, has died after a long struggle with bad publicity.

Dong Fang Ocean circa 2009, off the coast of Singapore. Copyrighted photo by Auke Visser, used with permission.

Exxon Valdez/Exxon Mediterranean/Sea River Mediterranean/S/R Mediterranean/Mediterranean/Dong Fang Ocean/Oriental Nicety being dismantled in Alang, India, 2012. Photo by ToxicsWatch Alliance.

Some Final Words of Thanks

It is not possible to list all of the contributors to NOAA scientific support, monitoring, and research in the last 25 years. Well, it would be *possible*—but not practical. There have been many, many scientists, vessel operators and crew, volunteers, students, and family members who made all of this work possible (we list a few of them at the very end of this document).

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Mearns, A. J. 1995b. NOAA's *Exxon Valdez* long-term shoreline ecosystem monitoring program: 1990-1994 trends. Proceedings of the 1995 International Oil Spill Conference, Long Beach, CA, pp. 977–978.

Mearns, A.J. 2014. A 24-year record of variability in cover of intertidal biota in western Prince William Sound, 1989 to 2013. Abstract and poster presented at the 2014 Alaska Marine Science Symposium, Anchorage, AK, Jan. 20-24, 2014.

Mearns, A.J., D. Crowther, R. Campbell, K. McLaughlin, P. Eiting, D. Janka, S. Pegau , and A. Doroff. 2014. Volunteers complete 24th year of rocky intertidal photo time series in western Prince William Sound. Abstract and platform paper presented at the 2014 Alaska Marine Science Symposium, Anchorage, AK, Jan. 20-24, 2014.

Mearns, A.J., K. McLaughlin, R. Campbell, J. Bodkin, T. Dean, B. Ballachey , and J. Harper. 2013. Joint effort adds 24th year to longterm rocky intertidal photo-monitoring of western Prince William Sound. Abstract and poster presented at the 2013 Alaska Marine Science Symposium, Anchorage, AK, Jan. 21-24, 2013.

Mearns, A.J. and G. Shigenaka. 1993. NOAA's long-term ecological recovery monitoring program: Overview and implications of recovery trends and treatment effects. In *Exxon Valdez* Oil Spill Symposium Abstracts, pp. 83-86.

Mearns, A.J., G. Shigenaka, M. Lindeberg, and J. Whitney. 2011. Recovery of a mussel reef in Prince William Sound 22 years after the *Exxon Valdez* oil spill and clean up. Abstract and platform paper presented at the 2011 Alaska Marine Science Symposium, Anchorage, AK, Jan. 17-20, 2011.

Mearns, A.J., G. Shigenaka, and J. Whitney. 2008. Colonization of a virgin shoreline in Prince William Sound, 2000 to 2007, compared to recovery of oiled and cleaned shorelines. Proceedings of the 2008 International Oil Spill Conference, Savannah, GA., pp. 743-747.

Michel, J., C. Henry, W.J. Sexton, and M.O. Hayes. 1990. The *Exxon Valdez* winter monitoring program results. Conference Proceedings on Oil Spills: Management and Legislative Implications, May 15-18, 1990, Newport, RI, pp. 396-407.

Michel, J., M.O. Hayes, W.J. Sexton, J.C. Gibeaut, and C. Henry. 1991. Trends in natural removal of the *Exxon Valdez* oil spill in Prince William Sound from September 1989 to May 1990. Proceedings of the 1991 International Oil Spill Conference, San Diego, CA, pp. 181-187.

Michel, J. and M.O. Hayes. 1993. Persistence and weathering of *Exxon Valdez* oil in the intertidal zone—3.5 years later. Proceedings of the 1993 International Oil Spill Conference, Tampa, FL, pp. 279-286.

Roberts, P., C.B. Henry, Jr., and G. Shigenaka. 1998. Documentation of weathered petroleum "bioavailability" to intertidal bivalve species after the T/V *Exxon Valdez* incident. In Proceedings of the Arctic and Marine Oilspill Program Vol 21b, 939-940.

Roberts, P.O., C.B. Henry Jr., G. Shigenaka, and A.K. Fukuyama. 1999. Weathered petroleum "bioavailability" to intertidal bivalve species after the T/V *Exxon Valdez* incident. Proceedings of the 1999 Oil Spill Conference, Seattle, WA, pp. 1002-1005.

Shigenaka, G., D.A. Coats, A.K. Fukuyama, and P.O. Roberts. 1999. Effects and trends in littleneck clams (*Protothaca staminea*) impacted by the *Exxon Valdez* oil spill. Proceedings of the 1999 International Oil Spill Conference, Seattle, WA, pp. 349-356.

Shigenaka, G. 2005. Perspectives on the *Exxon Valdez*. Proceedings of the 2005 International Oil Spill Conference, Miami, FL, 13 pp.

Shigenaka, G., D.A. Coats, and A.K. Fukuyama. 2008. Population recovery status of littleneck clams in Prince William Sound: An unexpected turn of events…. Poster presented at Alaska Marine Science Symposium, Jan. 21-25, 2008, Anchorage, AK.

Yender, R.A. 1997. Recovery of rockweed following experimental removal. In Proceedings of the 1997 International Oil Spill Conference, Fort Lauderdale, FL, pp. 1009-1010.

Books/Magazines

Easterbrook, Gregg. 1995. A Moment on the Earth: The Coming Age of Environmental Optimism. New York: Viking Press. 768 pp.

Holloway, M. 1991. Soiled shores. Scientific American 265(4):102-116.

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Michel, J. 1990. The *Exxon Valdez* oil spill: status of the shoreline. Geotimes, May 1990, pp. 20-22.

Michel, J. 1991. Prince William Sound, Alaska: the cleanup continues. Geotimes, March 1991, pp. 16-17.

Wheelwright, J. 1994. Degrees of Disaster. New York: Simon & Schuster. 352 pp.

Project Participants, 1990-2014

NOAA Program Management Team, *Exxon Valdez* **studies 1990-2014**

- Dr. Alan J. Mearns, 1990-2014
- Rebecca Z. Hoff, 1990-2004
- Gary Shigenaka, 1990-2014
- Ruth A. Yender, 1992-2003

Field sampling team members, Prince William Sound Long-Term Monitoring Program

- Greg Barats, Research Planning, Inc., 1990-1991
- Jim Blecha, Tenera Environmental, 1999
- Howard Cumberland, ERCE, 1992
- Dr. Herb Curl, NOAA, 1991
- Dr. Andrew DeVogelaere, Elkhorn Slough National Estuarine Research Reserve, 1994
- William Driskell, 1994-1996
- Dr. Thomas Ebert, San Diego State University, 1991
- Chris Ehrler, Tenera Environmental, 2000
- Dr. Ken Finkelstein, 1990-1991
- Dr. Allan Fukuyama, Pentec Environmental/University of Washington/FHTE, 1991-1995, 1997-2000
- Dr. Jerry Galt, NOAA, 1990-1991
- Rob Gilmour, Pentec Environmental, 1994-1996
- Peter Hague, Ogden Environmental, 1991
- Laura Hartline, U.S. Coast Guard Academy, 1990
- Dr. Miles O. Hayes, Research Planning, Inc., 1990-1992, 1994, 1997
- Charlie Henry, Louisiana State University, 1992, 1998
- Marc Hodges, NOAA, 1990-1991
- Rebecca Hoff, NOAA, 1991, 1992, 1994
- Dr. Jonathan Houghton, Pentec Environmental, 1990-1996
- Eiji Imamura, Marine Research Associates, 1997
- Dr. Ellery Ingall, University of Texas, 1995
- David Kennedy, NOAA, 1990-1991
- Scott Kimura, Tenera Environmental, 1997
- Dr. Terrie Klinger, University of Washington, 1997
- Steve Landino, Ogden Environmental, 1991
- Dennis Lees, Ogden Environmental/ERCE, 1990-1996
- Ed Levine, NOAA, 1997
- Mandy Lindeberg, NOAA/NMFS, 1998-1999
- Dr. Sandra Lindstrom, University of British Columbia, 1990-1996
- Scott Lundgren, U.S. Coast Guard, 1994
- Dr. Alan Mearns, NOAA, 1990-1996, 1999
- Stennie Medours, Texas Water Commission, 1990
- Dr. Jacqueline Michel, Research Planning, Inc., 1990-1992, 1994, 1997
- Scott Miles, Louisiana State University, 1997, 1999

- Todd Montello, Research Planning, Inc., 1992
- David Noe, Research Planning, Inc., 1990-1991
- Robert Pavia, NOAA, 1990-1991
- Debbie Payton, NOAA, 1990-1991
- Garry Phillips, Texas Water Commission, 1990
- Paulene Roberts, Louisiana State University, 1992-1997
- Susan Saupe, Cook Inlet Regional Citizens Advisory Council, 1997-1998
- Gerald Schimke, California Office of Emergency Services
- Debra Scholz, Research Planning, Inc., 1991
- David Serena, Research Planning, Inc., 1990-1991
- Gary Shigenaka, NOAA, 1990-1994, 1996-2000
- Debra Simecek-Beatty, NOAA, 1990-1991
- Bud Stanley, Texas Water Commission, 1990
- John Steinbeck, Tenera Environmental, 1998
- Steve Sturm, Research Planning, Inc., 1990-1991
- Howard Teas III, ERCE, 1990
- Jim Truman, Research Planning, Inc., 1990-1991
- Charles Valle, Ogden Environmental, 1991
- Ruth Yender, EPA, 1990-1991; NOAA, 1992-1993, 1995
- Scott Zengel, Research Planning, Inc., 1997

Invited scientists, student interns, and journalists, Prince William Sound Long-Term Monitoring Program

- Dr. John Armstrong, U.S. Environmental Protection Agency, 1991
- Jessie Cravens, Western Washington University, 1996
- Gregg Easterbrook, author, 1992
- Tamara Gage, University of Washington, 1995
- Cassie Hayes, Smith College, 1998
- Marguerite Holloway, Scientific American, 1991, 1996
- Dr. Ann Holmquist, Chevron/American Petroleum Institute, 1990
- Becky Lindgren, Smith College, 1998
- Fiona McNair, McGill University, 1997
- Dr. Robert Ozretich, U.S. Environmental Protection Agency, 1993
- Dr. Robert Paine, University of Washington, 1994
- Dr. Tim Reilly, Marine Spill Response Corporation, 1991
- Dr. Jennifer Ruesink, University of Washington/University of Victoria, 1996
- Cristina Rumbaitis-del Rio, Montgomery Blair High School, 1992
- Anna Sandoval, University of Washington, 1995
- Dr. Hiroo Uchiyama, National Institute for Environmental Studies (Japan), 1997
- Jeff Wheelwright, author, 1990

Scientists, volunteers, and vessels, Prince William Sound photo monitoring:

- Dr. Sarah Allan, NOAA, 2012
- John Bauer, Alaska Department of Environmental Conservation (ret.), 2008
- Evelyn Brown, Flying Fish Ltd., 2011

- Dean Dale, Genwest Systems, Inc., 2004-2005
- Jeff Lankford, NOAA, 2006
- Dr. Alan Mearns, NOAA, 2001-2010, 2012
- John Tarpley, NOAA, 2007
- Dr. John Whitney, NOAA, 2001-2010, 2012
- Chris Wooley, Chumis Cultural Resource Services, 2003
- David Goldstein, *Chinook*, 2001
- David Janka, *Auklet*, 2000, 2010-2013
- Chris Pallister, *Opus*, Gulf of Alaska Keeper, 2005-2007
- John and Joan Coombs, *Wave Walker*, 2004, 2010
- Mike Bender, *Explorer*, Lazy Otter Charters, Whittier, 2012
- Whittier Flotilla, Coast Guard Auxiliary, 2001-2007

Scientists, students, and volunteers, Kasitsna Bay experiment:

- Frances Brie Van Cleve, University of Washington School of Marine Affairs, 2004
- Melinda Chambers, University of Washington, 2002
- David Christie, NOAA/NURP, 2007
- Dr. Doug Coats, Marine Research Specialists, 1999
- Christopher Collins, 1999
- Leticia Conway-Cranos, NOAA/NMFS, 2010-2011
- Jill Coyle, University of Washington School of Marine Affairs, 2008
- Dr. Carolyn Currin, NOAA/Beaufort Lab, 2002
- Aleta Erickson, University of Washington School of Marine Affairs, 2005, 2007
- Dr. Allan Fukuyama, FHTE, 1999-2006
- Andrew Fukuyama, 2006
- Kathleen Herrmann, 2012
- Kris Holderied, NOAA/Kachemak Bay National Estuarine Research Reserve, 2007-2013
- Rebecca Hoff, NOAA, 1999
- Katrina Hoffman, Prince William Sound Science Center, 2012
- Dominic Hondolero, NOAA/Kachemak Bay National Estuarine Research Reserve, 2013
- Eiji Imamura, Marine Research Specialists, 1999
- Jennifer Johnson, University of Washington School of Marine Affairs, 2003
- Scott Kimura, Tenera Environmental, 1999
- Dr. Terrie Klinger, University of Washington, 1999-2013
- Mandy Lindberg, NOAA/NMFS, 1999
- Dr. Amy Merten, NOAA, 2001
- Mary Morris, 2009
- Erin O'Neill, University of Washington/Friday Harbor Lab, 1999
- Susan Saupe, Cook Inlet Regional Citizens Council, 1999
- Gary Shigenaka, NOAA, 1999, 2002
- John Steinbeck, Tenera Environmental, 1999
- Kyra Wickman, University of Washington/Friday Harbor Lab, 1999

Scientists, students, and volunteers, Lower Herring Bay experiment:

- David Dickey, Louisiana State University, 2000

- Chris Ehrler, Tenera Environmental, 2000
- Barbara Eiswerth, 2007
- Allan Fukuyama, FHTE, 2000-2012
- Andrew Fukuyama, 2006-2007
- Jennifer Johnson, NOAA/University of Washington School of Marine Affairs, 2003
- Mandy Lindeberg, NOAA/NMFS, 2000
- Dr. Amy Merten, NOAA, 2001
- Mason Shigenaka, 2011-2012
- Gary Shigenaka, NOAA, 2000, 2002, 2004-2005, 2007-2009, 2011-2012
- Are Strom, University of Washington, 2000

Scientists and volunteers, Prince William Sound clam study, 2007:

- Barbara Eiswerth
- Dr. Allan Fukuyama, FHTE
- Andrew Fukuyama
- Bonnie Luke, Marine Research Specialists
- Susan Saupe, Cook Inlet Regional Citizens Advisory Council
- Gary Shigenaka, NOAA

Vessels and owner/operators:

- *Nakat*, 1990
- *Legacy*, 1990
- *Carmen Rose*, 1990
- *Sound Investor*, 1990
- *Renown*, 1991-1992
    - Randy Becker
    - Eric Jackson
- *Good Times*, 1991, 1993-1995
    - Jack Gilman
    - Larry Gilman
- *Arctic Dream*, 1992
    - Bob Crocker
- *Outer Limits*, 1992, 1993, 1996
    - Mike Gilman
- *Kirawan*, 1996
    - Rick & Marty Anderson
- *Auklet*, 1997-2000
    - David & Annette Janka
- *DocWalloper*, 2001-2010
    - John Whitney
- *Sound Investor*, 2003-2006, 2008-2009, 2011-2012
    - Gerry Sanger
- *Babkin*, 2007
    - Brad von Wichman

Infauna and grain-size core samples, water salinity and temperature measurement, at monitoring site in Shelter Bay, Evans Island, 1999. Photo by Gary Shigenaka, NOAA.

Herring Bay, Knight Island, May 2007. Alaska ShoreZone photo by Mandy Lindeberg, NOAA Fisheries

March 2014

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Kathryn D. Sullivan, Ph.D.

Under Secretary of Commerce for Oceans and Atmosphere,
and NOAA Administrator

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Holly A. Bamford, Ph.D.

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