pancake. However, an overflight out to the buoy's position on Jan. 12 revealed the buoy within 10 miles of some pancakes. The January 12 and 13 overflights were extensive searches of the entire forecasted slick limits made by a NOAA C-130 plane. NOAA had supplied the plane at Capt. Hein's request because the Coast Guard's planes could not cover the required distance. The flights found oil more than 100 miles southeast of the wreck site.

Late in January, Hein planned another extensive search guided by the buoy. This time, the forecasted limits were to be divided into sections for coverage by three separate planes. But bad weather and a shortage of planes prevented the exhaustive search.

As the main body of the oil drifted southeast past the edge of the continental shelf, fear that it would turn around and hit land began to wane. There was, however, some concern over the ultimate dispersal of the oil that remained on the surface. Essentially, three possibilities were envisioned. One was the oil would get caught in the northeasterly Gulf Stream and get carried to Iceland or northern Europe. A second was that it would continue southeast through the Gulf Stream and into the Atlantic, where it also might eventually reach more southern parts of Europe. Finally, it was thought that oil might become entrained in some of the eddies that spin off the Gulf Stream. This oil, it was thought, might travel southwest along the edge of the shelf, possibly coming ashore near Cape Hatteras. The oil was so widely dispersed by now that it was likely some oil would follow each of the paths and others as well. It was realized, of course, that in
the months it would take to reach any of these land destinations
the oil would weather into extremely widely dispersed tarballs, whose
coming ashore would possibly not be noticed.

Two groups — the Coast Guard Oceanographic Unit and the USGS—
attempted to predict the long-term advection of the oil. But the
models were extremely crude and gave answers that were, at best,
speculative.

The Oceanographic Unit’s "model" was so crude it was called a
"speculative estimate" and not a forecast. It did not attempt to
predict which path the oil would take, settling instead for predicting
time travel times along various paths. The procedure used was to start
the oil on January 1 at 40°N, 65°W, near the leading edge of the
forecasted limits on that day. The "oil" was then moved under the
influence of the mean monthly wind vector (using a leeway of 1.2%) and
a sea current vector (assumed to include wind-induced surface currents).
The time step was one month. The Oceanographic Unit estimated that its
time travel times, shown in Figure 6.3-1, could be off by a factor of 2.

For long-term projections the USGS could no longer use its prepared
models because by January the oil had already moved out of the lease
area. So a new, simpler model was prepared. Rather than use a
lag-one transition matrix, winds were sampled randomly from monthly
wind roses. Either no current or the monthly prevailing current was
used, in proportion to the persistence of the current. Both wind and
current data were obtained from the U.S. Navy Marine Climatic Atlas
for the North Atlantic (Meserve, 1974). The time step was increased to
a day. A deflection angle of 20° to the right was added to the 3.5°
wind factor to account for the increased importance of the Coriolis
effect over larger distances.

The USGS used the data buoy position of January 1 as the starting
point for its multiple trajectories. It updated these predictions using
the buoy's position on February 1 and March 1. All these runs are
shown in Figure 6.3-2. Notice the big difference between the January
and March forecasts. The USGS attributed this to a three-way fork in
the Gulf Stream near 40°N, 65°W. A small difference in the short-term
movement before arrival at this fork could make a huge
difference in the long-term trajectory. Hence, the initial January
and February projections were as uncertain as the "forecasts" made by
the Oceanographic Unit.

The other trajectory-related activity to take place in January
was the deployment of seabed drifters. This activity was the last
of those left over from the discussions and worry following the breakup
of the tanker on December 21. Around the time of the breakup,
Clem Griscom, Saul Salla and Steve Olsen of URI's Coastal Resources
Center attended a meeting sponsored by the governor of Rhode Island.
The meeting was concerned mainly with the danger to that state.
Driving back from the meeting, Griscom became concerned that the oil
might sink and thus reach land. This was at the time when it was
widely thought that the oil would sink, and Griscom had heard somewhere
that the specific gravity of the oil was .996. So Griscom thought it
might be valuable to deploy plastic seabed drifters as early warning of
FIGURE 6.3-2: USGS Six-month forecast of oil trajectories made in January (top), February (middle) and March. Initial point is the position of the NOAA satellite trackable buoy. (from Wyant et al., 1977)
the landfall of oil. It is not surprising that Griscom would think of this, because he had been using the drifters for the previous year in a study of the effects of dumping on Brown's Ledge, east of Martha's Vineyard.

Griscom obtained some money from the university and ordered 1,000 drifters from the manufacturer, Insul-Tab in Woburn, Mass. Insul-Tab already had a logo with URI's return address, so it was merely a question of printing up 1,000 drifters. Redwood Wright of the NMFS office in Woods Hole, also desiring to deploy drifters, arranged for URI to have an extra 1,000 printed up (with URI's return address) for use by NMFS.

The 2,000 plastic yellow drifters with red stems arrived December 30. On January 4, Griscom brought rubber bands, candy "life savers" and leaf bags for deployment of the drifters. He assembled the drifters into batches of 25. Around the stems of each batch he wrapped a rubber band. He looped the ends of the rubber band through a metal washer and through a lifesaver. When the batches were dropped overboard, the washer would serve as a weight to carry the drifters to the bottom. Shortly after they arrived there the candy would dissolve, releasing the rubber band, and the drifters would be free. On January 6, Griscom deployed his drifters by helicopters in groups of 150 at 6 locations along the hypothesized path between the wreck and Rhode Island. These locations are shown in Fig. 6.3-3. The northern line (6,4,2) roughly
FIGURE 6.3-3: Location of Griscom's seabed drifter releases. Contour is in fathoms. All releases made Jan. 6 except No. 1, made Jan. 19.
followed the 15-fathom contour and the southern group (3,5) the 25-fathom contour. Griscom took Bumpus' (1973) word that outside of 25 fathoms, the bottom flow was predominantly offshore.

NMFS deployed its drifters in batches of 5 at 41 stations on a cruise of the Delaware II from January 4 to January 10. Except for the deployment of the drifters, the cruise was virtually a repeat of the Delaware's December cruise, only on a large scale. 43 stations were covered, although some additional planned stations were dropped owing to bad weather. Stations were pre-selected at random to cover once-contaminated areas and control areas and various depth strata. Once again the most recent slick map was used to determine the oil's boundaries. The stations sampled and the activities conducted, the same as on the first cruise, are shown in Figure 6.3-4.

6.4 Cod Stomach Oil and Other Biological Discoveries

One additional cruise to assess the effects of oil on the fisheries took place from February 17 to March 7. The cruise was a joint venture of NMFS and the Polish Institute of Sea Fisheries. A Polish vessel, the Wieczno, was used. It had been in the area as part of a bilateral fisheries agreement whereby Poland, which fishes off Georges Bank, provides a research ship for 4 months a year, according to Kenneth Sherman of the NMFS Narragansett Laboratory.

The crew again followed the same procedures followed on the two Delaware II cruises, on an even grander scale. The area of investigation encompassed Nantucket Shoals, the Great South Channel and Georges Bank south to the 200-meter contour and east to 66°50'W. The cruise
FIGURE 6.3-4: Delaware cruise stations, January 4-10. Dashed line shows oil boundaries estimated from January 3 slick map.
involved 2 phases: In the first phase fish trawls were made at 30 stations spread over the entire cruise area. In addition, benthic and sediment samples were collected at each station using a ring net and pipe dredge attached to the trawl and a separate Dietz-Lafond grab. Once again some samples were frozen for hydrocarbon analyses, some preserved in formalin for biochemical and pathology studies. Maturation levels were logged and 83 stomachs excised.

The same 30 stations and 46 others were then resampled for the second phase. In this phase plankton tows were conducted, additional sediment samples taken and seabed drifters (5 per station) deployed. Small amounts of tarballs were caught in every neuston (surface) tow, although surface oil was never visible during the tows. Stations sampled are shown in Figure 6.4-1.

Work on the samples collected from the Delaware II cruises, meanwhile, had been started at the various laboratories of the Northeast Fisheries Center.

In Narragansett the zooplankton collected in the .333 mesh oblique bongo tows of the December cruise were sorted by species just as in routine MARMAP operations. Ray Maurer then made the organisms transparent using lactic acid and examined them under a dissecting microscope for oil contamination. He noticed contamination ranging from 0% to 61% for a separate species at individual sites. As Figure 6.4-2 shows, there seemed to be no correlation between the per cent contaminated at the station within the oil and those outside it. The contamination was of three types. One was ingested droplets,
FIGURE 6.4-1: Wieczno Cruise Stations (from NMFS cruise report).
FIGURE 6.4-2: Abundance (top) and contamination of zooplankton sampled on first Delaware cruise. Figures in parentheses indicate number of organisms examined.
found either in the gut or the feces. This finding was not surprising since it was known that copepods could ingest oil droplets and excrete them (Freagarde et al., 1971). Another was external contamination and a third was mandibular contamination (oil adhering to feeding appendages). There was no way of telling, explained Maurer, whether the oil had hurt or killed the contaminated organisms. Nor was there any way of telling what effect contamination of zooplankton, a major part of the food chain, would have on fish stocks. The study, said Maurer, consisted of "just observations."

At Woods Hole, meanwhile, 305 stomachs from fish of 16 species caught on the 2 Delaware cruises were being painstakingly emptied and the contents examined by Richard Langton and Ray Bowman. They were mainly looking for oil, to see whether fish had ingested oil-soaked benthic invertebrates. While they were doing this they catalogued the contents of each stomach and grouped them according to fish size and species. Frankly, recalled Bowman, the scientists had not expected to find any oil in the stomachs and their early work bore this out. But it was right near the end when oil showed up. "You could smell it in the room when the stomach was opened up," Bowman said. Actually, oil was found in 3 stomachs. Two belonged to cod, both collected at station 29 of the January cruise, almost 30 miles southwest of the wreck site, far away from the surface contaminated area (See Figure 6.3-4). One of these cod stomachs was eventually sent to Seattle for full analysis. Oil was also found in a little skate stomach at station 36, 30 miles southeast of the wreck in the oil--contaminated
area. In all 3 cases the oil measured no more than 1 cc. Bowman estimated, and had entered the stomach on amphipods.

In Milford, Connecticut, Dusty Gould and Fred Thurberg were attempting to discover any sublethal effects of the oil spill. It was generally known that subsurface and bottom oil does not always reach high enough concentrations to be lethal, especially to mobile fish which can avoid the oil. However, low concentrations could still cause sublethal effects such as a general weakening of an organism such that it becomes more vulnerable to other stresses, more susceptible to predation, unable to reproduce, etc. If these effects vary among species the composition of the local ecosystem may change. In general, sublethal effects, while not as immediately obvious as immediate mortality, can be significant.

Thurberg and Gould picked several indices of sublethal effects. Thurberg analyzed the blood of 211 fish collected on the January Delaware cruise for ionic balance of the blood serum. He also examined the respiration rates of almost 100 scallops and mussels caught in the field and brought back alive. Gould examined fish and bivalve tissues for subtle biochemical changes such as a shift from aerobic to anaerobic metabolism and enzyme repression.

The results were somewhat mixed. The biochemical tests, said Thurberg, did not show any obvious effects on the organisms from the contaminated areas as compared to those from the clean areas. The blood serum tests did show some disruption of ionic balance. The bivalve tests showed a 25% repression of respiration in mussels from
beneath the spill as compared with those caught outside the spill and a 12-15% depression in scallops. However, Thurberg said, the difference would probably not hold up statistically since there were too few samples. "All we can get from this is an indication," he said. Subsequently, the Wieczno cruise samples were examined and the same indication of sublethal effects did not seem to be present. This may have indicated the organisms recovered. On the other hand, Thurberg said, it may be that the organisms in the spill area during the Wieczno cruise, especially the groundfish, were not the same ones that had been there during the spill. This is especially likely because many samples were taken close to the boundary between the contaminated and clean areas.

Perhaps the most important studies of all, however, were those of the ichthyoplankton. This is so for two reasons. First, they are the life stages of fish most likely to be affected by the oil. This is because they (especially larvae) are in general more sensitive to oil and other stresses (Rice et al., 1977), because they remain at the surface with the greatest proportion of the oil, and because as plankton they lack the ability to move away from oil.

The other reason is that the survival of eggs and larvae is probably the major determinant of the size of fish stocks. Egg and larval mortality, explained George Kelly of NMFS's Woods Hole lab, is extremely high, perhaps 99.9%. Small changes in this figure, say a few tenths of one percent, may account for millions of fish, although the actual relationship between egg mortality and fish population is
somewhat fuzzy.

Fish eggs and larvae collected from the .505-mm surface tows and the .505-mm oblique bongo tow on the first Delaware cruise were sorted and counted by station. Only cod and pollock eggs were found, along with larvae of 6 species. Arlene Longwell of the Milford Laboratory examined 232 eggs, half the eggs collected, for cytological and genetic damage. By determining arrested cell development in the embryos, Longwell could determine not only mortality but moribundity as well.

Longwell found that about 25% of cod eggs and 46% of the pollock eggs were dead or moribund. Moribundity and mortality varied by station, with no easily observable difference between clean and contaminated stations. Longwell also observed that oil was adhering to the chorion, or outer membrane, of many eggs, particularly pollock. At Station 9, 60% of the pollock eggs had oil adhering to them and 94% were dead, perhaps indicating some connection between oil exposure and damage.

One of the puzzling findings of Longwell's work was the fact that pollock eggs seemed more susceptible to coating by oil and to damage than cod eggs. Exactly the opposite would have been expected, since the cod eggs were in a much earlier stage of development.

To help figure this out and to get a better idea of oil's effects on eggs, several laboratory experiments were conducted jointly by the NMFS and EPA laboratories in Narragansett. In one test, an attempt was made to induce membrane contamination of eggs by mixing eggs and oil.
The tests proved unsuccessful. Another experiment tested the effect of the water-soluble fraction of No. 6 oil on cod eggs. Since the Argo Merchant oil was not available, a standard No. 6 oil was used. Since the concentrations after the Argo spill were not known, initial concentrations of 500, 100 and 10 parts per billion of total extractable hydrocarbons were used. These hydrocarbons were allowed to evaporate freely. Cod eggs were exposed at 3 embryonic stages — 4-6 hours, 3 days and 7 days. The highest concentrations caused death, delayed development and reduced heartbeat. The intermediate concentrations caused only the sublethal effects and the lowest initial concentrations caused no noticeable effect after 10 days.

By March, also, two batches of fish tissue samples had been sent to Seattle for hydrocarbon analysis. Because of the great costs involved ($700 per tissue sample, said Kelly) the NMFS scientists were very stingy in sending samples. Only those obviously oiled or most likely to be oiled were sent. To further reduce costs, tissues from three fish of the same species collected at the same station, or from three separate organs in the same fish, were combined into a single sample, Kelly said.

6.5 The Search in the Sediments

The outgrowth of the NOAA-sponsored meeting of January 3 and 4 was a series of three cruises by URI’s Endeavor in late January and February. Eva Hoffman of URI recalled that she had attended the two-day NOAA meeting as a mere onlooker, only to find that NOAA had no one to conduct the cruise it was planning. URI's oil spill researchers had
been planning a cruise of their own. They gladly supplanted whatever money they were planning to use on that cruise with NOAA money.

The cruises aimed mainly at determining the extent of sediment contamination. The first two of these cruises especially were confined to sediment sampling (for hydrocarbons and benthic organisms), and water column sampling (for hydrocarbon concentration and oil droplet distribution).

Selection of sampling stations for the first of the three cruises -- done at a January 21 meeting -- was an elaborate affair. The URI group assumed that oil would most likely be found in areas covered by the slick for the longest time, or in areas covered by the slick when the sea state was high or in shallow areas. Unlike the Oceanus crew, they did not consider the types of sediments in their planned sampling area, reasoning the sediments were relatively uniform.

The group drew two rectangles (A & B in Figure 6.5-1) which encompassed two areas covered by the oil for at least six days. They divided each rectangle into square-nautical-mile tracts and chose at random 6 tracts from block A and 24 from block B. Another three stations, labeled C were chosen in shallow areas, yet another three (labeled D) in areas covered by oil during high sea states. The first two stations from the first aborted cruise were labeled D, and two stations between blocks A and B labeled F. Letter G was saved for stations to be added en route based on the results of on-board screening by Dick Jadamec using ultraviolet fluorescence spectroscopy. It was hoped to sample 50 stations in all.
Figure 6.5-1: Station selection for URI benthic survey (from Grose and Mattson, 1977).
Unfortunately, the cruise, which left January 26, turned into a repeat of the Endeavor's short-lived December effort. Once again weather and equipment malfunctions shortened the trip, this time limiting it to 5 stations. Had the equipment been working perfectly, chief scientist Eva Hoffman estimated, ten stations might have been sampled, but the weather would still have blocked further work.

On February 9, however, the Endeavor tried again and managed to sample 38 of the stations picked for the January cruise. Three sediment samples were taken at each station using a Smith-MacIntyre grab. No box cores were taken, as had been recommended at the Woods Hole planning session, because no box corer was available. URT's was broken and NOAA did not supply one despite the recommendations, Hoffman explained.

In addition, a hydrocast was made at each station using Niskin bottles to collect water samples at 1 meter, 6 meters, and near the bottom. Two samples for benthos were taken using a scallop dredge.

The sampling found oil at three stations in the immediate vicinity of the wreck or within 12 miles to the southwest. These locations are shown in Figure 6.5-2. Two of these stations were "G" stations, those added en route based on quick screening results.

Also shown in Figure 6.5-2 is the location of Evergreen station B, sampled way back on Dec. 22. This station was found to be uncontaminated at the time. From this, and from the fact that only very low (250 ppb) concentrations of hydrocarbons were found in the water column, and this
FIGURE 6.5-2: Sediment sampling results as of mid-February (after Grose and Mattson, 1977)
mostly the cutter stock, it was hypothesized that the oil found on the bottom had leaked directly into the sediments from the bow section as it danced along the bottom, and that the oil-contaminated sediments were drifting southwestward with the prevailing bottom currents.

As for the diamond-shaped marks in Figure 6.5-2, they are stations 13 and 14 from the second Oceana cruise of December 28-29. Hearing from URI that these stations now had oil-contaminated sediments, a small group of WHOI scientists returned to the area early in March. According to Howard Sanders and George Hampson, sampling indicated a three-fold reduction in benthic life in the area. This finding, they said, was never followed up for lack of funds.

When the contaminated samples were examined in the laboratory, Hoffman said, it was found that the oil did not coat the sediments. Rather, pollution was in the form of tiny tarballs generally ranging in size between .2 and 1.0 mm. These tarballs could be shaken loose from the sediments. When formalin was added to parts of the samples to preserve them for biological work, some of the droplets rose to the top of the formalin and spread out into tiny slicks.

The tar balls were distributed in patches, Hoffman said, and these patches were found throughout the 5-cm depth of sediment obtained by the Smith-MacIntyre grab. When the samples were removed layer by layer, there did not seem to be any regular variation of tarball concentration with depth, said Hoffman.
Perhaps the most significant finding of the Endeavor cruises was that the oil did not seem to reach the sediments in areas covered by the surface slick. These cruise results and subsequent screening, however, could not indicate how much oil did reach the bottom in areas where it was found. The areal extent of contamination was still not known, since no stations had been sampled to the southwest of those at which oil was found. The depth of contamination was still not known, since the Smith-MacIntyre grabs did not reach beyond contaminated depths. And the concentrations of hydrocarbons were not known since the screening results were extremely crude. The thin layer chromatography, for instance, could not distinguish between hydrocarbon levels in some of the samples judged contaminated and the levels in the baseline samples from Oceanus stations 13 and 14. Concentrations of oil exceeding 100 ppm could not be measured at all by the ultraviolet fluorescence technique. These methods, of course, were not meant to give more than a crude indication of oil's presence or absence.

To better determine the areal extent and depth of penetration of sediment contamination, the Endeavor undertook another cruise from February 22 to February 27. Eight box core samples were taken in contaminated areas (see Figure 6.5-3) to determine the depth of oil's penetration. In addition, 53 Smith-MacIntyre grabs were made. Many of the stations were to the southwest of the wreck, as is also indicated
FIGURE 6.5-3: Stations on final Endeavor cruise, Feb. 22-27. Squares indicate box cores, triangles indicate Smith-MacIntyre grabs (from URI cruise report).
in Figure 6.5-3.

This fourth Endeavor cruise also branched out extensively into biological sampling, most of it concentrated within an area 5 miles south, east and west of the wreck. Some 55 vertical zooplankton tows and 6 phytoplankton tows were made for studies on species abundance and diversity. Eighteen neuston tows were made for studies by NMFS of the effect of oil on eggs and larvae.

Nine scallop dredge samples were taken for benthos. In addition, the box cores and Smith-MacIntyre grabs were to be used for a number of biological investigations. Among them was to be an attempt to correlate sediment oil levels with those found in benthos.

These benthic samples and scallop dredges were brought back to the lab and looked at quickly. Some mollusks were opened and oil, later shown to be Argo Merchant oil, was found between the meat and the shell. About 30 apparently affected mussels were frozen for future analysis. The scallop dredges netted only two crabs, one dead, one sick. These seemed affected by the oil.

Very little of the detailed biological and chemical work was done, however, since there was no money for it. While the planning meeting at Woods Hole in early January had estimated a cost of $255,000 for sample collection and analysis, URI was given only $60,000 for its first successful cruise (its third cruise overall). This barely covered sample collection. For the fourth and last Endeavor cruise,
URI was given only $23,000 out of a requested $60,000. Nor did the ERDA project chip in after the second cruise, since the cruise objectives (except for droplet distribution measurements) were not directly related to the goals of the project. In fact, Mason Wilson himself, the prime mover in the early days after the grounding, withdrew from participation in the URI response after the first cruise for that reason and because he felt he was losing control of the integrated team response.

So most of the samples sat preserved at URI and were worked on sporadically, when an interested faculty member or student could find time between funded projects. The process of analysis proceeded this way into the summer of 1977. "It's like a hobby with most of us around here," said Hoffman on July 11, "because we have to make our bread and butter other ways."

The same thing was true at WHOI, MIT and NMFS. Everyone had other obligations and it was becoming clear to them that the government was losing interest in the Argo Merchant spill, no doubt because the lack of clearly visible effects had diffused its political impact. This seemed to disillusion many of the academic scientists, who thought they had been urged to continue their work upon false promises of payment. "I think I'd be very, very leery about getting involved in another spill," said WHOI's Howard Sander, "and I think everyone would -- and precisely the people they need." And Milgram of MIT
 echoed, "I won't get involved next time, I won't go out on a limb."
Others would not go as far in precluding future participation, but in
any case, by the end of March it was clear that there would be no
long-term study of the Argo Merchant oil spill and that even the short-
term work would remain unfinished.

6.6 Finis

The elusive bow section, by the way, was finally located on
February 10, during the first successful Endeavor cruise. The bow
lay in 60 feet of water at 40°59.1'N, 69°25.8'W, about 2700 yards
southeast of the stern section.

Two Navy and two Coast Guard divers descended that day and found
the bow upside down, its forecastle imbedded in the sand. The shell
plating and decking on the starboard side were ripped and torn aft
of the forecastle break. Debris was strewn along the 2700-yard long
line that ran from bow to stern. The divers entered a tank on the
starboard side and found no oil except a few small pockets which
clung to the bulkheads and suction lines.

With that, the Coast Guard's response dwindled to its end. The
day after the bow was found, Capt. Hein terminated the contracts
with Coastal Services and Jetline on Nantucket and ended the Coast
Guard's beach patrols. He informed NWS that its special wind forecasts
were no longer required and he determined that the scheduled overflights
were no longer needed. From then on, the area near the wreck could
be checked by the twice weekly fishery patrol flights.

On February 8, two days before the bow was found, Hein had ended the Oceanographic Unit's daily forecast, although he requested that the 5-day outlook continue. No oil was sighted between February 11 and March 1, so on that day he discontinued the 5-day outlook as well.
CHAPTER 7

SCIENTIFIC EVALUATION OF POST-SPILL ACTIVITIES

The preceding chapters have chronicled the large and somewhat confused scientific followup to the Argo Merchant oil spill. This chapter will evaluate the scientific quality of what was done, since in the end, this is what is most important. Moreover, it will attempt to do this in a manner that will shed some light on the matter of what to do after future spills. Rather than merely saying which activities were scientifically good and which poor, it will where possible point out why the activity was good or poor and how helpful the activity was in achieving the various goals of a scientific response. The lessons gleaned from this chapter will then be summarized, and their future implications explored, in the final two chapters.

The quality of the response from a scientific viewpoint is a function of two factors — the internal quality of each activity and the overall mix of activities. This chapter will start with an activity-by-activity review and then conclude with some remarks on the overall collection of activities.

The quality of each activity is a function of some well-known factors. Among them:

METHOD: This includes things like samplers, analytical techniques, modeling schemes, etc. Some samplers for instance, take less contaminated samples, some modeling techniques are better than others. Associated with the method is a resolution. For instance, we might
ask how sensitive an analytical method is for detecting small changes in hydrocarbon content, or a viscometer to small changes in viscosity, etc.

**SPATIAL ISSUES:** There are 3 issues related to spatial coverage.

One is the overall extent of the coverage, either in 2 or 3 dimensions, e.g., did sampling, modeling, or overflights cover the entire oiled or affected area. A second concern is the spatial resolution: Were plankton tows and sediment grabs spaced closely enough and well enough to prevent aliasing yet account for patchiness? Is wind field or jet necessary for an oil spill model? The third concern is whether sample locations were chosen in general? For instance, in looking for oil in the sediments, were logical areas and adequate control areas sampled, were drift cards dropped in logical locations, etc.?

**TEMPORAL ISSUES:** These are analogous to spatial factors in many ways.

One issue is temporal coverage — both starting and stopping point. Starting point is particularly important for short-term studies. As the chronology has shown, some efforts were greatly diminished by tardiness in implementation. For longer-term assessments the stopping point is of prime concern. Certain effects of the spill might not be noticeable for several years and will go unnoticed if the study stops before that. The third temporal issue is that of synoptic. With the water constantly moving and the oil constantly changing, it is often useful to obtain data at many spatially
disparate points at the same time. The degree of synopticity is some indication of the quality of the endeavor.

It should be pointed out that the same activity may serve many functions and that a given level of "quality" may suffice for one purpose but not for another. Collection of hourly wind data at one point over the spill area may suffice as model input but would never do to measure the leeway for 10 minutes at a location several miles from the source of wind data. With this in mind, we can begin the scientific review of the scientific response.

7.1 Surface Slick Trajectory Studies

These activities include slick surveillance, tracking, modeling and the various oceanographical and meteorological activities needed to support them. We discuss each in turn.

7.1.1 Slick Surveillance

The Argo Merchant spill was one of the most extensively observed, tracked and mapped spills in history. Activities related to surveillance included daily mapping flights by the Coast Guard and SOR team; other flights for color and false color infrared and visual photography; satellite imagery; helicopter flights for small-scale, detailed studies of pancake growth and movement; observations and photography of the slick from below by divers; and the deployment of numerous drifters.

As the preceding chapters have shown, many of these observational activities were inspired, conducted or recruited by the SOR team.
Among these were the pancake observations, the below-slick dive and the NASA overflights. Many others arose from individual initiative or at the request of the OSC. Flying over a spill, after all, is one of the most obvious of activities, and, especially on the days immediately following the grounding and breakup, the sky was so cluttered with aircraft belonging to the Coast Guard, the press, scientists and the public that someone on board the on-scene Cutter Vigilant had to direct traffic. Observed one airborne scientist, "Conditions out there were like coming into Logan Airport."

Most of the remainder of this subsection will discuss the daily slick mapping (Section 4.4) which was clearly the most important of the surveillance activities. In fact it is probably fair to say that it was one of the most important activities of all, contributing to all the post-spill goals. For damage assessment, the maps were instrumental in sampling station selection for almost all cruises. And as the assessment continues, knowledge of the areas contaminated will be needed to correlate observed damage with oil pollution, both scientifically and legally. As for assisting the OSC, Capt. Hein said that knowledge of the oil's position was the most valuable information to him. The maps made the on-line modeling possible and sometimes were used in place of the models. This is because all that was often required was a general idea of the slick's position, for which a map, never more than a day old, was sufficient. Finally, for pure research purposes, the biggest use of the maps so far has been for model verification studies.
At the same time, the maps were not very useful for other purposes because the method used was subject to several limitations:

**VISIBILITY:** The ability to detect and map the slick was limited to times when it could be seen. For starters this eliminated nighttime surveillance. In the case of the Argo Merchant spill, this was not a severe problem, mainly because the slick was more than a day away from shore at most times and because nothing was being done to remove the slick anyway. It seems possible, though, that nighttime surveillance ability could be useful, though probably not overly crucial, in future spills.

Even during the day, however, visibility was often a problem. The cloud base, which ranged from 300 feet to 1000 feet during most of the spill period (Grose and Mattson, 1977) occasionally interfered with the 500-foot-high flights. Storms were another problem. A third difficulty was the sun's glare, although said Deaver, a solution to this problem was eventually discovered. The solution was to orient the tracklines parallel to the sun's path. This way at least one side of the plane would be in the shade and have a good view on each leg.

**WEATHER:** In addition to limiting visibility, the weather also interfered with the flights in the same way it did with most of the cruises — by making flight conditions exceedingly rough or impossible. Only two flights were grounded by rough weather in December, on December 28 and December 29. Since engine failure cancelled the December 30
overflight, a three-day block was missed. The timing was somewhat unfor-
tunate because the December 27 map had been one of the most complete and
by December 31, the slick was already too large for accurate mapping and
had started to dissipate. It was also somewhat unfortunate because
December 28 and 29 were big cruise days and it might have been inter-
esting, though not terribly so, to view the sampling locations in
relation to the slick boundaries.

**HUMAN ERROR AND CAPABILITY:** The fact that mapping was done by the
human eye severely limited the mapping capability. For one, it
restricted the spatial resolution of the map. Having to scan 5 miles
to the side of him as the plane flew by at 145 knots, Deaver could not
sketch the slick or a pancake field in great detail. He could only
make general indications of coverage (e.g., pancakes, heavy coverage,
thin sheen). As a very general indication of the spatial resolution, we
can compare the map of December 19 (see Fig. A-3 in Appendix) with the
NASA false color photo-mosaic of the same day (see Grove and Mattson
(1977), Photograph 22). We can see that Deaver easily picked up the
tidal excursion, of the order about 10 kilometers in length. But
he missed the vortex formation in the wake of the tanker, a phenomenon
with a length scale of several hundred meters.

Secondly, in making these rough judgments of percent coverage,
thickness of coverage and pancake sizes, it appears Deaver's estimates
were prone to err on the high side. When the SOR team tried to use one
of the maps to calculate surface slick volume, the result was an order
of magnitude greater than the total capacity of the Argo Merchant.
If it is assumed that little of the oil entered the water column or bottom sediments and little evaporated (which is easily corrected for), then a good estimate of surface slick volume would have served as an estimate of total spill volume. Such an estimate might have told the Coast Guard as early as late December that there was little oil left in the bow. This might have permitted the response to end much sooner, saving the governments lots of money. This, of course, is true provided only that there really was little oil left in the bow and that the Massachusetts officials and the public believed it and were willing to accede to a reduction of stand-by cleanup forces.

SYNOPTICITY AND SPATIAL COVERAGE: Mapping of the outer slick boundaries did not suffer from the frailties of human capability to as a great a degree. This is because Deaver merely had to note passing over a boundary on the strip chart to place the boundary within the navigational accuracy of Loran A. There were some other problems with mapping the overall extent and shape of the slick, as opposed to individual boundaries. One was that by January the huge area covered by the oil prevented the flying of systematic tracklines, and the spatial resolution and accuracy of the maps suffered somewhat. The other was the problem of synopticity arising from the fact that the oil was continually moving under the slick. The greatest distortion arising from this would be in the wind's direction, the direction of maximum velocity, and it is relatively simple to estimate how large this distortion might be. Deaver generally started from the back of the slick (near the wreck) and zig-zagged toward the southeast,
taking about 8 hours to reach the leading edge. Assuming for argument's
make that the oil moves at 3% of the wind speed, it can be seen that
with a 10-knot wind the mapped slick will be 2.4 nm (nautical miles)
longer than the actual slick was at any instance and 4.8 nm longer under
a 20-knot wind. If the map is assumed to represent the slick at the
midpoint of the flight, both the back and leading edge of the slick will
be off by 1.2 and 2.4 nm for the two winds respectively. If the spill
is continuously emanating from the source, only the leading edge will be
off by that amount. Clearly this is within the overall accuracy of
other parts of the system. The presence of strong currents might
increase the distortion from lack of synopticity.

It would be relatively simple to measure the overall accuracy
of the visual slick mapping against synoptic photographs. Since these
were not available to the authors, a general idea was obtained by
comparing two visual "maps" of the slick made at the same time by
different observers. Such a comparison is shown in Figure 7.1-1
using Denver's map and the one made by EG&G and Aero-Marine Surveys,
Inc. (Raytheon, 1977) on December 23. This was the date of the BLM
contractor's most extensive overflight. While no actual map was
made, oil observations were recorded at accurate times and locations
along the tracklines shown.

The figure shows that both observers generally agreed on the
presence or absence of oil. The two maps disagree in their position-
ing of the leading edge of the slick (along 41°N) by about 5 nm, a
difference of less than 5% of the length of the slick. Almost a
mile of this discrepancy might be accounted for by the fact that Deaver flew over the boundary about an hour before EG&G. (Winds at the time were 25 knots directly from the west.) Hence one might conclude that the general uncertainty in oil boundaries is a few miles. Note, also, however, that EG&G spotted some oil to the far northeast, where Deaver did not fly. This leaves open the possibility that Deaver might not have mapped all the oil since he generally covered only the Oceanographic Unit's forecasted limits. As will be seen in the next subsection, these limits were not always reliable.

In summary, then, it can be seen that the visual overflights made up in frequency, thoroughness, and quick turnover time what they lacked in sophistication, accuracy and capability. The adequacy of the maps depended on their use. They were certainly adequate for model verification studies, since the models treated only advection and only a general notion of slick shape was required. Even the leading edge of the slick did not have to be very accurate for model verifications because there was so much uncertainty about when the oil at the leading edge actually left the tanker. Another problem is the distance of the leading edge from the source of wind data. Because of uncertainties like these, hindcasting could not be used to make fine distinctions between models (such as 3% vs 3.5%) anyway. For these kinds of determinations small-scale observations are needed with very localized and short-term winds and current measurements, as was done in the SOR team's leeway tests. The maps were also good enough for cruise planning and would have been adequate, if necessary,
for placement of cleanup equipment.

The maps could not show thickness and percent coverage and were thus of no use in oil budget calculations. And had spreading and weathering models been available, the maps would not have been of much use for input or model verification, also because of the inability to measure thickness and pancake sizes. However, those models will also require somewhat better estimates of spill rates than the gross estimates used in the Argo Merchant case.

It might be thought that either photography or other more esoteric means of remote sensing might have been used instead of visual mapping or as a useful supplement to it. Some of these techniques were indeed tried but according to the SOR team's James Mattson and Cmdr. Morgan of the Oceanographic Unit, little of it was of very much value. The Landsat imagery taken on 3 days by NASA either was obscured by clouds or could not detect oil, although, said Morgan, it was somewhat helpful in determining currents. The photographs, both IR and visual, were somewhat useful in smaller scale observations, such as individual pancake movement over short distances, but not as useful as originally thought for refining Deaver's maps.

The SOR team's photos were not that useful, said Mattson, partly because the time each photo was taken was not recorded accurately enough to permit accurate determination of position. This will be corrected in the future by having the date and time recorded directly
on the film.*

The EPA photography was standard stereoscopic mapping photography, with a 6" focal length and an altitude of 1,000 feet, the ground resolution is 2 feet, according to Bill Fowler of EPA's Remote Sensing Operations Branch in Las Vegas. From that altitude, each 9x9 color photo covers an area about 1500 feet on a side (about 10 photos needed to cover a square mile). With cloud cover as low as it was the plane would have had to fly lower, with correspondingly better resolution and smaller areal coverage per photo. It might seem that such photography could have been a useful supplement to visual mapping, although too many photos would have been needed to map the entire slick. The photo interpreter could probably have distinguished heavy slick from crude oil, although probably not well enough to estimate thickness accurately.

Yet the 300 photos taken on 3 separate days did not add much to the visual maps. Part of this was again due to cloud cover. In particular, virtually all of the photos from December 19 are obscured by clouds. Another reason that they were not particularly useful for mapping is that no one really thought of using them for this purpose. According to Fowler and to John Conlon, EPA's RRT representative during the Argo Merchant response, the photos were taken at the request of the OSC and RRT simply to provide photographic documentation of the

* EG&G did have such a system in which 3 cameras were activated at once — two vertical looking belly-mounted cameras and one which took a snapshot of the Loran C monitor. At the time he was interviewed Mattson had not yet seen the EG&G/AMSI photos, so his comments do not apply to them.
spill, no doubt because the National Contingency Plan calls for such documentation. EPA's chartered pilots, said Fowler, didn't even bother to record the altitude or coordinates of each photo. EPA was merely after photographs which showed the presence or absence of oil, period. With such an intention, it is not surprising that the photos could not easily be used for more sophisticated purposes.

It should be pointed out that a much more sophisticated system for spill surveillance was available in prototype form only a few months after the Argo Merchant spill. The Coast Guard's new Airborne Oil Surveillance System includes a variety of sensors designed to allow surveillance under most weather and light conditions. These sensors include (Maurer et al., 1977) side-looking mapping radar, low light level television, a passive microwave imager, and IR and UV line scanners. The sensor combination is expected to permit estimates of oil area and thickness.

7.1.2 Oceanographical and Meteorological Measurements

The success of the mapping and modeling activities depended heavily on the forecasting and collection of ancillary meteorological and oceanographical information. They merit at least brief mention.

WIND AND WEATHER FORECASTS: The several special forecasts made by NWS for the Fishing Rip area (Section 3.3) were among the most useful of activities following the spill. The computer wind forecasts made on-line trajectory modeling possible. The weather and sea state forecasts were directly useful in planning dives and overflights for salvage, cleanup and scientific purposes. The forecasts began early
in the response and were available as frequently as needed. The accuracy of the wind forecasts will be discussed in the next subsection.

**WIND AND WEATHER OBSERVATIONS:** Perhaps the most useful measurement of all was the hourly observation of on-scene winds by the Coast Guard cutters. The frequency of these measurements was urged by the SOR team. On-scene winds were necessary for modeling and will be useful in the future for model verification studies and perhaps also for studies of other processes that depend on wind, e.g., evaporation and dispersion of oil.

It has been mentioned that successful on-line oil forecasting required frequent and immediate feedback from oil observations. In the same manner, successful wind and weather forecasting required feedback of on-scene wind and weather observations. "It's awfully, awfully important to get on-scene weather," said Robert Lynde of the NWS at Logan Airport. However, while oil slick maps were given to the slick forecasters, the needed on-scene weather information never got through the confusion to NWS. It was several weeks, recalled Lynde, before the feedback system began functioning smoothly.

**CURRENT METERS:** Some measurements of the long-term tidally averaged current in the area would have been useful as input into models or for hindcasting. Many of the models included such a residual current, but there was great uncertainty as to what the current should be. The CEDDA model used a current of 0.25 knots to the west, while the Oceanographic Unit finally settled on one of 0.25 knots to the
The USGS used data from Bumpus (1973) which indicated a northwesterly flow of about 0.8 knots. And in summarizing what was discovered about oil transport during the spill, Grose and Mattson (1977) reported a current of 0.6 knots to the southeast on top of the wind-driven oil drift.

It was noted (Section 5.3) that the potential usefulness of the current meters was reduced substantially by the fact that the data was not concurrent with the on-scene wind data nor with the best slick maps. However, even had they been installed more rapidly, they would not have been able to measure residual surface drift because they must be placed at depths of at least 5 meters to avoid severe contamination of the data by waves. In addition, it is not clear the current meters used were capable of sufficient resolution to detect the magnitude and direction of the mean surface drift amidst the variability related to the tidal and wind-driven currents.

Another way of determining residual surface drift is with Lagrangian drifters, which we turn to next.

**LAGRANGIAN DRIFTERS**: Many types of drifters were employed both for slick tracking and for Lagrangian current measurements. There were datum marker buoys, drift cards, dye patches, a satellite-trackable buoy and big fat plywood sheets.

Briefly, the only drifter of substantial usefulness was the satellite-trackable data buoy (Section 6.3). It was used to track the oil out off the shelf in January when overflights became more difficult. It served to guide overflights and served in the oil's stead for one
long-range model. The reasons it was useful for tracking and long-
term drift measurements were that it lasted a long time and could
always be found.

All the other drifters suffered from either detection difficulties,
a short lifespan, or both. The dye current probes gave measurements
that were of such a short-term nature that they reflected the tide
almost exclusively. They were essentially worthless as independent
current measurements, being useful only in conjunction with SOR team's
leeaway experiments, as when it was necessary to sort out oil, wind
and water velocities on a small scale. The plywood boards were never
found; the drift cards could not be identified well enough. The datum
marker buoys were a little better and somewhat useful, lasting up to
3 days and being trackable by radio.

Most of the drifters were deployed relatively early in the history
of the grounding. This is because much of it was part of the pre-
established plan of the SOR team and EG&G or, in the case of DMB's, a
somewhat standard procedure for the Coast Guard. Here is a case where
planning seems to have backfired in that much of these drifters were
deployed automatically, without a thought to their real usefulness.
"The SOR team was not prepared to work in a tidal regime," Mattson
commented months later, "We should have thought of that."

The drifter that was useful was not thought of until December 28.
Not surprisingly, the person who thought of it was the SOR team's
Peter Crose, who had helped develop one such buoy while working at the
NOAA Data Buoy Office in Mississippi. Here it would have been useful
to have pre-planned for this and deployed one or more much earlier.
7.1.3 Modeling

Among the most publicized of the activities following the oil spill and one of the ones to get underway the earliest was the oil trajectory modeling. The Argo Merchant was truly a modeler's oil spill, because of the number of models run, the extensive observations of slick movement and the collection of the ancillary meteorological and oceanographical data necessary for input and verification. To review, there were two models run in a forecast mode in real time (by the Coast Guard Oceanographic Unit and the Coast Guard R & D Center). There were five risk assessment models run, and an additional probabilistic forecast mode using Bumpus' (1973) drift bottle data (which can be considered a physical, as opposed to a numerical model). There was one subsurface trajectory model and two long-range forecasts. Many of these models were also eventually run in a hindcast mode for verification. In addition, the author is aware of one model run solely in the hindcast mode, that of Arthur Tingle et al. (1977) of Brookhaven National Laboratory. Tingle received only day-old wind data, not forecasted winds, preventing his model from being of any use in the response. As has been mentioned, because of the extensive slick mapping it is likely that many other models will be tested by hindcasting the Argo Merchant spill.

Table 7.1-1 contains a summary of these models. As can be seen, they have many features in common. All deal exclusively with 2-dimensional advection. None includes slick dissipation, even as merely a sink term (i.e., reducing the volume of the surface slick but paying no attention to where the oil goes after it leaves the
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**TABLE 7.1-1:** Summary of models used during Argo Merchant spill response (after Grose and Mattson, 1977).
slick). Most of the models considered the slick to be a point or a series of points, although the Oceanographic Unit did capture some of the effects of slick growth by advecting the points separately under a spatially varying current field, thereby applying an effective dispersion to the slick. Regarding advection itself, the fixed wind factor approach was the overwhelming, though not unanimous, choice. The models did differ, however, in statistical use of wind data for the probabilistic forecasts and in choice of forces (e.g. tides, currents) in addition to the wind-induced drift. None of the models considered wave-induced motion explicitly, which according to Stolzenbach et al. (1977) may be of the same order of magnitude as wind--induced motion. However, wave-induced motion is presumably contributing to the fixed wind drift factor or to leeway factors.

A chart similar to Table 7.1-1 appears in Stolzenbach et al. (1977) and is reproduced as Table 7.1-2. The 12 models contained therein represent the state of the art in late 1976. Comparison of the two tables clearly shows the high extent to which the Argo Merchant models reflected the prevailing state of the art. Of the 12 models in Table 7.1-2, 10 do not include weathering or vertical movement. All but three use a fixed wind factor approach, and of those that don't, one uses merely a wind factor that can vary with wind speed, one uses an Ekman approach similar to the Oceanographic Unit's and one uses a depth-averaged circulation model similar to Tingle's. Only one of the 12 explicitly considers the influence of waves. Nine of the 12 do include spreading, generally using the formulation of Fay (1969, 1971),
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<td>5. Coast Guard</td>
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<td>6. SHADOCK</td>
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<td>7. Coast Guard</td>
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<td>11. Narragansett Bay</td>
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<td>12. Puget Sound</td>
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**TABLE 7.1-2:** The characteristics of several state-of-the-art oil spill models as of late 1976 (from Stolzenbach et al., 1977).
but Stolzenbach et al. (1977) found this formulation to be generally inapplicable, especially in rough seas.

The Argo Merchant models, then, clearly reflected the state of the art. Indeed, it was only by running simple or already existing models that the output could be produced as quickly as it was. Perhaps the only new feature in any of the models was the Oceanographic Unit's inclusion of a separate leeway figure of 1.2%, measured on-scene, in addition to the surface current. Previous models have either added 3% of the wind to the calculated surface current or no wind at all.

It now remains to discuss how useful these models were to the spill response. The following two subsections address only the most important of the models, namely the Oceanographic Unit's on-line model and the various short-range risk assessment models.

7.1.3.1 On-Line Forecasting

The accuracy of the Coast Guard Oceanographic Unit's on-line forecasts (Section 4.4) can be judged easily from Figures 7.1-2(A-F). These figures compare the forecasts and the observed slick for December 22 through December 27, the days immediately following the tanker breakup for which slick maps are available. The forecasts can best be called erratic. Some days, like December 22, the model came fairly close in predicting the observed oil configuration. Other days it was extremely far off. The model was generally horrendous in predicting the exact shape of the slick and the location of patches. It was somewhat better in predicting the more general slick limits, although
FIGURE 7.1-2(A,B): Comparison of Oceanographic Unit's on-line forecast with observed slick. Dashed line (--) shows actual model forecast, the dot-dashed line (---) the slick limits which were to contain all surface oil.
FIGURE 7.1-2(C,D): Comparison of Oceanographic Unit's forecasts for December 24 and December 25 with observed slick.
FIGURE 7.1-2(E,F): Comparison of Oceanographic Unit's on-line forecast with observed slick. Note that December 27 forecast is for 1 a.m. while observed slick map is for 1 p.m.
in this too it was erratic. The December 23 limits were 30 miles too long. This is technically excusable since the limits were supposed to err on the conservative side. More serious were the times when oil was found outside the limits, which occurred to some degree on all the days shown in Figures 7.1-2. On December 27 the oil extended 60 miles beyond the limits shown, which were for 1 a.m. Since the map is for 1 p.m., some correction must be made for the extra travel time. Winds at the time were about 30 knots from the west. If the oil moved at 3% of the wind speed* for 12 hours under the influence of this wind, at 1 a.m. the leading edge would have been only 10.8 miles behind its 1 p.m. position. Hence the limits would still have been short by some 50 miles. One can imagine the consequences in another spill if such limits were relied upon to state that oil heading toward shore would still be 50 miles away in the morning.

It is instructive to review the possible sources of error in the forecasting. One is the error in the model formulation itself, in other words, how much the forecasts would be off even if it had perfectly correct input (e.g., wind and current) data. This cannot be judged without extensive hindcasting studies. Suffice it to say that the model is about as sophisticated as any in existence and could not have been

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*The Oceanographic Unit's model did not actually use the so-called "3 per cent rule." It used 1.2% of the wind speed plus a calculated wind-induced surface current. It is thus unfair in some sense to speculate based on the 3% rule, but doing otherwise would have required re-running the complicated Ekman surface current model. Hence 3% will be used as a rough indication of oil movement (either actual or forecasted by the model) to give rough ideas of various errors.
improved much even if it were faulty.

Other errors arise from the overall on-line modeling and mapping system by which winds, currents, and slick positions were supplied and used. To quickly review, the forecasts were made for 12 or 24 hours ahead, starting from essentially brand new slick positions each time a new map was received. The modeler would hindcast from the previous day's map using observed winds and then forecast ahead one day using forecasted winds.

One possible explanation for the disagreement between the forecast and observed slick is that the maps themselves were in error. Nor did they correspond exactly to the time for which the forecasts were made since they were not synoptic. These errors were discussed in Subsection 7.1.1 and found to introduce an uncertainty of only a few miles, certainly not enough to account for what is shown in Figure 7.1-2.

Another error likely to be small is the use of a single wind field (the Oceanographic Unit used up to three forecast winds at one time, but only one observed wind). Even if the model moved off perfectly in response to the wind, the hourly wind at the wreck site is not likely to be exactly the same as the between-hourly winds 100 miles away. For a very quick and dirty estimate of the uncertainty introduced by spatial variability, we can consider the difference in winds observed on-scene and at the Nantucket Lightship, 30 nautical miles away. Fredrick Godshall of NOAA's CEDDA in Washington, D.C. found that on-scene winds could best be estimated from lightship winds by

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subtracting 13° and multiplying by 1.17 (Grose and Mattson, 1977). For a 20-knot wind at the lightship, we might therefore expect a 23.4-knot wind on-scene, deflected 13°. Allow these 2 winds to advect 2 dots of oil from the same starting point at 3% of their speed. At the end of 48 hours the 2 dots would be about 4 nautical miles apart, a not-very-significant amount considering other errors in the system.

A more serious error is in the treatment of the residual current, which could not be determined adequately during the spill. At first the Oceanographic Unit tried to hindcast it on a daily basis, which had the effect of throwing all sorts of other errors into this current. This would be permissible if these other errors were constant from day to day, which they weren't. Later the current was deleted altogether. As seen in the previous subsection (7.1.2), estimates of this current ranged from .8 knots to the northwest to .6 knots to the southeast. If these 2 currents were used to advect 2 dots of oil from the same starting point, at 48 hours the dots would be an incredible 60 miles apart. The real error from neglect of the current was likely much smaller than this. In hindcasting, the Oceanographic Unit found its best value was .25 knots to the northeast. If this had been included in the forecast all along, the forecast positions would have differed by 12 miles from what is shown in Figure 7.1-2.

The biggest source of error, however, is no doubt the wind forecasts. Grose and Mattson (1977, p.37) present some data on wind forecast errors. Roughly, winds forecast 6 hours ahead were off by an average of about 6 knots in speed and 35° in direction. For 24 hours
the figures were 7 knots and 40°. Performing our 2 dot advection using a 20-knot observed wind, a 26.5 predicted wind, and a 37.5° angle between them, the dots would be 11.6 miles apart in 124 hours.

This is not the whole story, however. About 10% of the forecast winds were off by more than 90°, and 10% by more than 15 knots. It is clearly these huge wind errors that account for the huge errors in the oil forecast. The very erroneous limits for Dec. 27 were made on the basis of the forecasted onshore winds of December 26 (Section 5.1) which didn't materialize. Similarly, it has been seen that the December 21 forecast (Figure 4.2-1) was invalidated by an expected change in wind direction.

This is important, because wind forecasts are generally out of the hands of the spill modeler. Even if his model is perfect in all other respects, it is still likely to be off by 10 miles or so (if a 24-hour lead time is used) and possibly by much more than that.

Barring improvements in wind forecasting, the best way to get around this is to update the forecasts as often as possible substituting the most up-to-date forecast and observed winds. This requires an efficient system with a quick turnover time, which was not in existence for the Argo Merchant spill. In the Argo Merchant case the model was continuously being developed, computerized and refined as it was being used. Lt. Frydenlund, who developed and ran the model, said he was capable of making a 24-hour forecast every

*In actuality errors in different time steps within this 24-hour interval might partially cancel one another. A much more sophisticated analysis is possible, but would require either the actual forecasts and observed data or more statistics as to any biases in the errors.
6 hours. But only he could do that, because the model was in prototype form, precluding the possibility of round-the-clock updates. After the spill response ended, Frydenlund automated the model so that virtually anyone could run it with the computer plotting the forecast slick configuration. The model now is capable of a 48-hour forecast every 3 hours, said Frydenlund.

How useful to the Argo Merchant response was the on-line forecasting on the whole? Not very. This is largely because no cleanup was attempted and the largest use of such a model is likely to be positioning of equipment. With no cleanup, about all that was needed was some general idea of the position of the oil and whether it was heading toward or away from shore. The maps would generally suffice for the former purpose and the wind forecasts for the latter. Scientists, too, used the map for cruise planning rather than the model.

Even had a cleanup been attempted, the model would not have been sufficient. When oil was heading toward shore, Capt. Hein had the SOR team send to Colorado for drift cards rather than rely solely on the computer. Capt. Hein said he did not think the model was sufficiently refined to be relied upon until more than 2 weeks had elapsed.

The main use of the on-line model was to guide Joe Deaver's overflights. It has been noted that this constituted quite a closed cycle --- the model would guide the overflights and the flights would provide maps for the model. Clearly the maps were more valuable to
the model than vice-versa. In fact, to hear Joe Deaver tell it, the model was sometimes of no help at all. "The computer didn't tell me anything at the beginning," he recalled. "I was told to 'Go find oil, Joe, and come back with information.'" By the end, he said, the limits had grown so large as to encompass "the whole Atlantic." The models would have been more helpful to him, he said, if he had been given a high-probability area rather than merely the outer limits. Flying to the extent of the limits sometimes doubled the distances needed to map the oil.

In summary, about the most obvious thing that can be said about the on-line modeling was that it was not on-line soon enough to be of much use.

7.1.3.2 Risk Assessment Models

Unlike the forecast models, a risk model cannot be judged on how its predictions compared with the actual path taken by the Argo Merchant spill. While all the models predicted a high probability of the subsequently observed southeasterly oil drift, this in no way "confirms" the models, just as a landfall of oil would not have disproved the models. The only way to "verify" the risk assessment models during the Argo Merchant incident could be to observe numerous identical Argo Merchant spills. This, of course, cannot be done, but decisions must nevertheless be made on the basis of these probability estimates. Therefore, the relevant question is how much the estimates can be trusted for decision-making. This depends largely on the nature of both the deterministic and stochastic parts of the model.