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GhostNet marine debris survey in the Gulf of Alaska – Satellite guidance and aircraft observations

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ABSTRACT

Marine debris, particularly debris that is composed of lost or abandoned fishing gear, is recognized as a serious threat to marine life, vessels, and coral reefs. The goal of the GhostNet project is the detection of derelict nets at sea through the use of weather and ocean models, drifting buoys and satellite imagery to locate convergent areas where nets are likely to collect, followed by airborne surveys with trained observers and remote sensing instruments to spot individual derelict nets. These components of GhostNet were first tested together in the field during a 14-day marine debris survey of the Gulf of Alaska in July and August 2003. Model, buoy, and satellite data were used in flight planning. A manned aircraft survey with visible and IR cameras and a LIDAR instrument located debris in the targeted locations, including 102 individual pieces of debris of anthropogenic or terrestrial origin.

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1. Introduction

The NOAA Marine Debris Program (http://marinedebris.noaa.gov/) defines marine debris as: "any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment or the Great Lakes." Fishing debris, especially derelict fishing gear, is widely recognized as a serious threat to vessels at sea (i.e., collision or prop entanglement) as well as to fish, sea birds, marine mammals and turtles (i.e., entrapment and drowning). Ubiquitous in the marine environment, marine debris, especially long-lasting plastic debris, has become a global problem (Atlantic Ocean: Law et al., 2010; Gulf of Mexico: Barnea et al., 2009; Mediterranean Sea: Aliani et al., 2003; Indian Ocean: UNEP, 2009; Southern Ocean: Barnes et al., 2010; Pacific Ocean: Morishige et al., 2007). In addition, grounded debris, particularly fishing nets, can cause physical damage to reef and beach environments and continue to entangle and kill reef and surf/beach inhabitant species. In particular, young Hawaiian Monk Seals, an endangered species, and Northern Fur Seals, a depleted species, are particularly vulnerable to entanglement in nets and plastic debris (Donohue and Foley, 2007; Fowler, 1987; Henderson, 1990; Zavadil et al., 2007).

The GhostNet Project, a research collaboration of Government, academia, and industry, was conceived in 2000 with the goal of developing instrumentation, remote sensing techniques, and a search and recovery strategy to cost-effectively detect, track, and eventually remove marine fishing debris in the open ocean. It was postulated that extracting derelict nets at sea would

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contribute to (1) preventing "ghost fishing;" i.e., continuation of net entrapment of living species by lost or abandoned fishing gear, (2) decreasing derelict net damage to reef and beach ecosystems, and (3) reducing the cost of removing nets from reefs and beaches. NOAA uses small boats and divers to cut nets off of the coral reefs of the Northwestern Hawaiian Islands (Dameron et al., 2007). During the period 1996–2009, 671.45 metric tons of derelict fishing gear were extracted from the reefs of the Northwestern Hawaiian Islands (NOAA Marine Debris Program, 2011). After studying the historical reports of marine debris distribution in the North Pacific (Mio et al., 1990), the GhostNet project targeted the Gulf of Alaska, the Southeastern Bering Sea, and the North Pacific Subtropical Convergence Zone (STCZ) north of Hawaii as areas that could benefit from at-sea detection and removal efforts. The Gulf of Alaska was the first region surveyed (in 2003), and served as the prototype for subsequent field programs in the North Pacific. The second and third field programs targeted the STCZ north of Hawaii in 2005 and 2008 and have been documented in Pichel et al. (2007) and McElwee and Morishege (2010), respectively. The Gulf of Alaska (GoA) pilot survey, documented herein, (1) provided information on marine debris in a region which has not been extensively surveyed, (2) served to develop and refine techniques for detection of possible convergent areas and for observing marine debris, and (3) provided practical experience concerning which satellite and aircraft sensors were the most useful for marine debris surveys. The techniques developed in the GoA field program are quite generally applicable for marine debris surveys in other ocean areas from the tropics to high latitudes.

The GoA field program consisted of a series of nine aircraft flight legs crossing portions of the GoA during the period July 20, 2003 to August 2, 2003. These flights were the culmination of 2 years of study of historical debris distribution, extensive project planning, development of a buoy system for marine debris tracking, aircraft remote sensing instrumentation testing, tailoring of an ocean geographic information system (GIS) for environmental analysis and debris tracking, analysis of historical and current satellite remote sensing data, and flight planning and preparation. This paper will (1) describe what was known historically of the distribution of marine debris in the GoA, (2) present satellite observations of likely debris convergence zones, (3) describe the aircraft survey, (4) detail the results of the survey flights and describe the debris that was found and its distribution, and (5) detail the lessons that were learned in this initial survey which paved the way for subsequent GhostNet surveys.

2. Methods

The following strategy was adopted for the marine debris surveys conducted by the GhostNet Project: (1) Locate general ocean areas of probable debris accumulation by researching historical studies, running circulation models and analyzing wind and current information to determine areas of convergence. (2) Track drifting buoys, either those already available or those deployed by GhostNet, to validate convergence, track actual nets at sea (i.e., those tagged with buoys), and determine local ocean circulation patterns. (3) Develop methods of analyzing co-located buoy, satellite, and meteorological data within a GIS environment to develop and refine the flight plan and help in the interpretation of survey results. (4) Observe identified areas of probable debris accumulation using satellite remote sensing imagery and measurements to observe ocean features indicative of convergent processes. (5) Test and refine sensor systems, observation strategies, and analysis/charting systems to determine an effective method of accurately observing and recording debris by aircraft survey. (6) Just prior to field debris surveys, consult weather and ocean forecasts and satellite wind and cloud data to verify that weather conditions are conducive to debris survey operations; i.e., cloud ceiling is higher than flight altitude, minimal sun glint, winds have been light (or at least less than 12 m/s) for the past 24 h, winds are forecast to be light (or at least less than 12 m/s) for the survey region during the survey times, waves are small to moderate (root-mean-square slope less than about 0.2 with few breaking waves), and there is sufficient illumination for visual observations (solar zenith angle less than 60 degrees). Determine the regions with the best viewing conditions and adjust the flight plan accordingly. (7) Fly manned instrumented aircraft over areas of ocean convergence with weather and ocean conditions conducive to aerial surveys, and observe and document individual debris objects and the general distribution of debris in the targeted areas. (8) Develop a system using a debris recovery ship and an unmanned aerial system (UAS) that could be used to cost-effectively locate and retrieve debris at sea on an operational basis.

The first 7 elements of the above strategy were followed for the GoA survey and are detailed below. Number 8 has been a focus for GhostNet development subsequent to the GoA survey, but was not an activity of the GoA survey.

2.1. Historical debris and oceanographic studies and drift model data

Activities within the current NOAA Marine Debris Program and the GhostNet Project to study marine debris distribution are recent efforts built on marine debris studies which have been underway sporadically for a number of decades. Some of these surveys were detailed in a series of marine debris conferences held in Hawaii in the 1980s (Shomura and Godfrey, 1990; Shomura and Yoshida, 1985). In the late 1980's, the Japanese Government conducted marine debris surveys of the North Pacific and Alaska waters (Mio et al., 1990). This was an extensive study of the North Pacific utilizing 32 vessels over a period of 2 years, surveying a total of 165,288 nautical miles. In 1987, 46,706 debris sightings were recorded with the distribution given in Table 1.

Debris density was high in coastal regions and in the region bounded by 25°N to 30°N latitude and 130°W to 170°W longitude. Unfortunately, the GoA was not well surveyed, so no firm conclusions can be drawn as to debris density there. Debris observations in the vicinity of the Aleutian Islands and in the Bering Sea were predominately floating seaweed. Dahlberg and Day (1985) found 10 objects in one transect of the Gulf of Alaska, predominately at 55°N (a transect length and width estimated by Ribic and Bledsoe (1990) to be approximately 1240.8 km long and 50 m wide). In a study of benthic debris in the waters around Kodiak Island, Alaska (Hess et al., 1999), marine debris obtained in 625 research bottom trawls during 1994–1996 were analyzed and summarized. Fishery-related items (most commonly plastic fishing line, bait jars and crab pots) made up between 38% and 46% of the total debris items recovered; however, more metal cans were recovered than any other type of debris. Debris densities within inlets and bays,

Table 1
Type of marine debris and percent of total debris observed by shipboard observers in the North Pacific during the year 1987.[a]

Description of object	Percent of total (%)
Fishing net debris	0.7
Other fishing gear	5.9
Styrofoam	14.0
Other plastic products	18.3
Drifting logs or lumber	7.9
Floating seaweed	42.7
Other (principally glass products and empty cans)	10.5

[a] Data for Table 1 taken from Mio et al. (1990).

particularly near population centers, were significantly greater than densities outside of inlets. For example, fishery-related debris items had a density of 20.1–25.0 items/km^2 inside inlets and only 4.5–11.1 items/km^2 outside of inlets. Although there have only been a few limited debris surveys in the GoA, fisheries studies, scientific cruises, beach clean-up efforts, and tracking of many deployed buoys have provided much practical information on debris location and movement. Beach surveys (King, 2008) indicate that some beaches are perennial "hot-spots" for collecting marine debris. These include islands, capes, or points which present a shoreline at an angle to the prevailing current and which tend to collect debris particularly on the side facing the current or storm winds. Examples are Kruzof Island, Kayak Island, and Middleton Island (Johnson, 1990) and Gore Point on the Kenai Peninsula. These all stick out into the Alaska Current or the Alaska Coastal Current. See Figs. 1 and 5 for the geography of the GoA and location of places referenced herein.

A summary of some of the practical knowledge derived from scientific surveys, beach clean-ups, and drifting buoy tracks follows (Stabeno, 2003). (1) Eddies, particularly their central cores, can collect and hold debris. (2) Islands and capes/points that stick out into the Alaska Coastal Current collect debris on the beach and in the sea grasses of island shoals. The lee side of these islands will often have semi-permanent eddies which also collect debris. (3) Current speeds through the Aleutian passes are very high (up to 340 cm/s). Debris does not tend to collect there or on the Aleutian Islands. (4) Certain bays of the Alaska Peninsula, Kodiak Island and the Shumagin Islands collect debris.

Surface circulation in the GoA (see Fig. 1) can be characterized as a subarctic gyre having a counterclockwise flow with water originating in the North Pacific Drift flowing easterly from Japan, and splitting near Vancouver Island into the southerly California Current and the northerly Alaska Current. Mean velocities in the Alaska Current, which flows in deep water along the shelf/slope break, are highest (15 cm/s) in winter and lowest (5 cm/s) in summer. The Alaska Current intensifies to the west into a western boundary current, becoming much stronger southeast of Kodiak Island, where it is now called the Alaska Stream (Muench and Schumacher, 1979). Freshwater input from rivers and coastal runoff which are substantial during early summer (snow melt) and in autumn (rainfall) along the northern coast of the GoA drive a separate, parallel, less-saline Alaska Coastal Current (ACC) which also flows counterclockwise, but very close to the coast (Stabeno et al., 1995). At 165°W, at the end of the Alaska Peninsula, the ACC is no longer distinguishable from the Alaska Stream, which then continues west on the southern side of the Aleutian Islands.

The Ocean Surface-Current Simulator (OSCURS), initially developed for fisheries studies (Wilderbuer et al., 2002; Duffy-Anderson et al., 2010), has been used to track marine debris in the North Pacific (Ebbesmeyer and Ingraham, 1994; Ebbesmeyer et al., 2007; Pichel et al., 2007) and was employed in this project. This model uses daily values of sea-level pressure from the 6-hourly model of the US Navy Fleet Numerical Meteorology and Oceanography Center. OSCURS calculates geostrophic winds from sea-level pressure and wind-driven surface currents from these winds. These currents are added to the long-term average geostrophic currents to get an estimate of surface current. The total drift of an object is calculated from surface currents and winds using a parameter (wind-current-speed coefficient) that describes the relative effects of wind on the object; objects that extend further out of the water are more sensitive to wind effects than objects with a lower profile. This model indicated that debris tracks would follow the Alaska Current, ACC, and the Alaska Stream along the northern periphery of the Gulf of Alaska and then along the southern shore of the Aleutian Islands. Some debris would then flow through the Aleutian passes, traveling north along the shelf break in the Bering Sea, moving toward the Pribilof Islands (Ingraham and Ebbesmeyer, 2000; Ingraham, 2003).

Three features of the current dynamics of the GoA became foci for the GhostNet survey: (1) the presence of long-lived eddies in the northern GoA, (2) the influence of Kayak Island on the local current regime, and (3) the presence of convergent shelf break fronts along the Alaska Current and Alaska Stream.

Long-lived eddies (some have been tracked for 3 years) are formed in the Alaska Current off the coast of Canada near the Queen Charlotte Islands (called Haida eddies; Crawford, 2002), near Sitka Alaska (called Sitka eddies; Tabata, 1982), near Yakutat, Alaska (called Yakutat eddies; Ladd et al., 2005a), or south of the

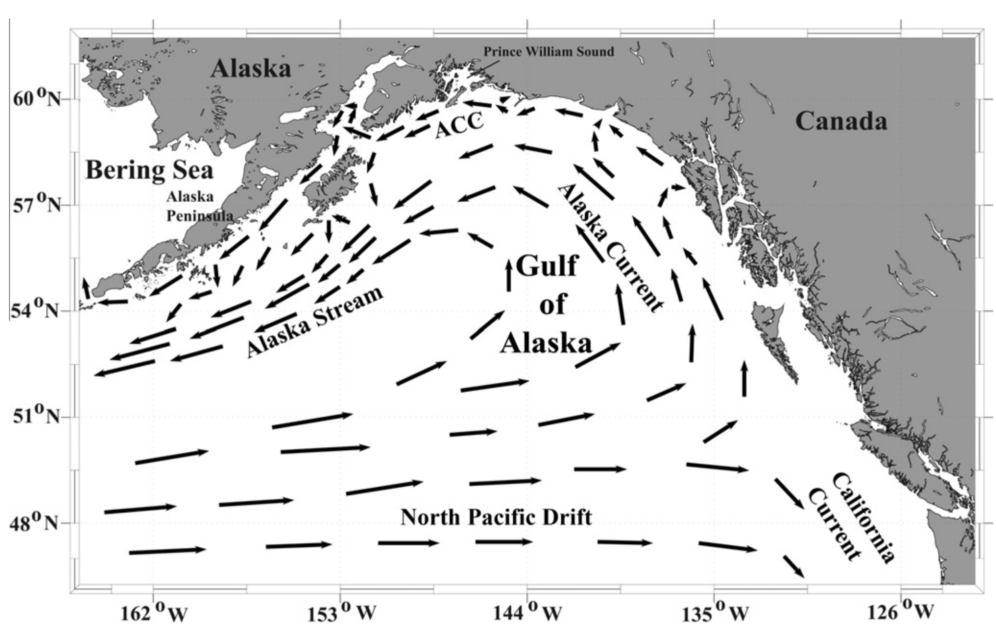

Fig. 1. Circulation in the Gulf of Alaska. Waters of the North Pacific Drift current either turn south as the California Current or north as the Alaska Current. This current follows the continental slope around the north of the Gulf of Alaska and then intensifies as a western boundary current past Kodiak Island and along the Alaska Peninsula. A parallel Alaska Coastal Current (ACC) flows close to shore driven by river input and coastal runoff (figure adapted from Dobbins et al., 2009).

Kenai Peninsula (called Kenai eddies; Rovegno et al., 2009). Haida eddies usually migrate to the west, straight into the middle of the GoA, but Sitka and Yakutat eddies tend to migrate west along the shelf/slope break at the northern end of the GoA to Kodiak and then south along the Alaska Peninsula. These anti-cyclonic eddies have warm cores and are less saline than their surroundings with positive sea surface height anomalies of up to 0.7 m and diameters of about 200 km (Crawford, 2002; Ladd et al., 2007). Observations of drifting buoys caught in these eddies result in measurements of eddy orbital period of 6–23 days, with orbital velocities between 0.02 and 0.32 m/s, and an eddy drift of 0.01–0.02 m/s. Other measurements (Ladd et al., 2007) indicate drifter speeds as high as 0.70 m/s with an average of 0.4 m/s. Although there have not been definitive studies, drifter behavior indicates that the eddy circulation is convergent at its core and divergent at its perimeter. Some drifters, mostly those shallowly drogued (15 m) are expelled from the eddy before completing one cycle around the eddy, whereas deeply drogued buoys (100–110 m) make many complete circuits of the eddy (Crawford, 2002). Other researchers report, however, that surface drifters with and without shallow drogues can be caught in these eddies, particular near the center of the eddy, and make many circuits (Ladd et al., 2007). In addition to these large long-lived eddies, smaller eddies and eddy-like features can entrain drifters (and marine debris).

Kayak Island, an island on the continental shelf in the northern GoA, extends from near the coast to the southwest within the ACC. This island diverts the westerly flow of the ACC to the south, with the result that vortices are created off the southern tip of the island with eddy-like circulation to the west, and easterly flow with eddy-like structures can form behind the island. Both of these features have been observed with drifting buoys (Muench and Schumacher, 1979).

Fronts are boundaries between water masses with differing properties (e.g., temperature or salinity). Fronts, which can be convergent or divergent, often form at the transition between the shallow coastal waters of the continental shelf and the continental slope leading to the deep ocean (i.e., the shelf break). These fronts, called shelf break fronts (or shelf/slope fronts), if convergent, can concentrate marine debris, and several of the GhostNet flights either crossed or followed along the shelf break. These fronts are narrow in a direction perpendicular to the shelf break (about 10 km) but can stretch for hundreds of kilometers along the shelf break (Wang et al., 1988). In a study of the North Atlantic Bight shelf/slope front, a convergence zone with a width of 10 km (approximately the same width as the front) was estimated to have a downwelling velocity of 20–36 m/day (Gawarkiewicz et al., 2001). These fronts can show up as temperature fronts in infrared (IR) satellite imagery or sea surface temperature (SST) maps (for an example, see Fig. 4b), as color or chlorophyll fronts in ocean color imagery, and as narrow linear or curved features of increased or decreased backscatter relative to the background in synthetic aperture radar (SAR) images (Johannessen et al., 1996).

2.2. In-situ data and GIS systems

In order to verify drift models and confirm convergent processes, two different versions of a low-cost drifting GhostNet buoy were developed for the GhostNet project. Five copies of the first model were deployed by the US Coast Guard during a Hawaii to Alaska transect in January 2003 in the vicinity of the STCZ, which was the original target area for the GhostNet project. A number of these buoys had antenna problems, so buoys with a modified design were developed. The new low-profile design was solar powered and user programmable. The redesigned buoys, however, were not ready for deployment prior to the GoA field program, but have been employed in subsequent GhostNet field activities. For the GoA survey, the GhostNet Project relied primarily on available satellite-tracked drifting buoys which were ingested into the GIS software system used for project data display to provide an indication of recent circulation patterns, and sometimes the location of eddies. Applicable to interpreting the GhostNet GoA results was a GhostNet buoy deployed in 2006 in the northeastern GoA at 58.15°N and 141.13°W within a small cyclonic eddy (i.e., not one of the long-lived anticyclonic eddies). This buoy stayed within the eddy for 35 days, from July 5, 2006 until August 9, 2006, and then exited and was carried by the Alaska Stream onto Kayak Island where it was beached on August 25, 2011 and finally recovered the following year. Fig. 2 shows the buoy track and a photo of the buoy ashore in the midst of a considerable amount of marine debris on the southeast-facing Kayak Island beach.

The GhostNet project used a number of different software systems for data display and analysis. The major system used for

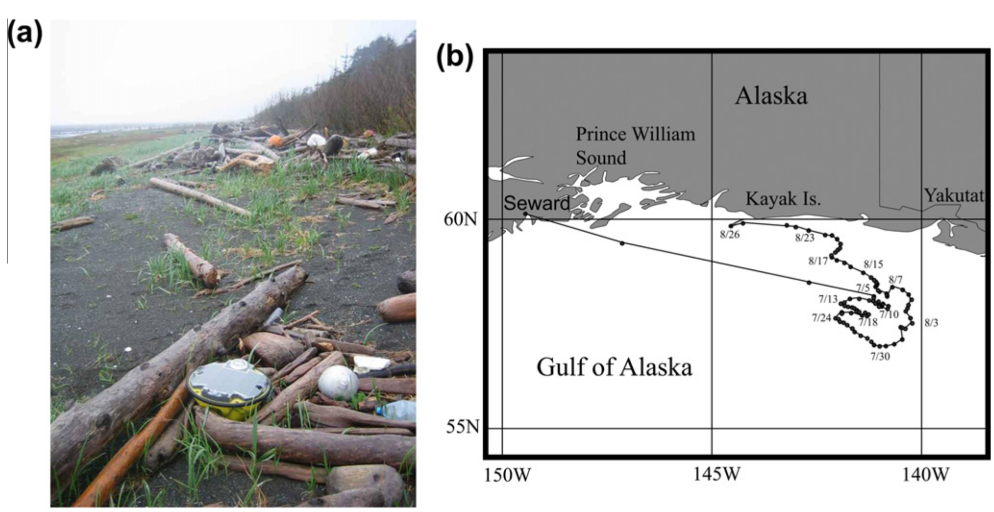

Fig. 2. (a) Debris washed ashore on the southeast coast of Kayak Island in the northern Gulf of Alaska, east of Prince William Sound. The gray-topped, yellow, tub-shaped buoy in the foreground is a GhostNet buoy released in the Gulf of Alaska in 2006 and tracked to and recovered from Kayak Island (Photo courtesy of Airborne Technologies Inc., Wasilla, Alaska). (b) Track of the GhostNet buoy shown in (a). This buoy was carried aboard ship from Seward, Alaska, released at 58.14°N, 141.13°W on July 5, 2006 within a small cyclonic eddy. The buoy exited the eddy 35 days later on August 9, 2006, then was carried ashore on Kayak Island on August 26, 2006. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Types of satellite data collected and analyzed for the GhostNet Gulf of Alaska marine debris survey (data were collected May–August 2003).[b]

Satellite	Sensor	Source	Frequency	Description
NOAA POES	AVHRR	NOAA CoastWatch	6 times/day	SST images
Terra/Aqua	MODIS	NOAA CoastWatch	4 times/day	SST images
NOAA GOES	Imager	NOAA CoastWatch	Hourly	SST images
Terra/Aqua	MODIS	NOAA CoastWatch	Twice/day	Chlorophyll images
RADARSAT-1	SAR	ASF	Occasional	SAR backscatter imagery
TOPEX/Poseidon, Jason-1, GFO	Altimeter	Univ. of Colorado	Daily	Sea Surface Height Anomaly maps

[b] Acronyms and data sources in Table 2: ASF – Alaska Satellite Facility, University of Alaska Fairbanks; (http://www.asf.alaska.edu/); AVHRR – Advanced Very High Resolution Radiometer CoastWatch (http://coastwatch.noaa.gov/cwn/index.html); GFO – Geosat Follow-On; GOES – Geostationary Operational Environmental Satellite; MODIS – Moderate Resolution Imaging Spectroradiometer; NESDIS – National Environmental Satellite, Data, and Information Service; NOAA – National Oceanic and Atmospheric Administration; POES – Polar Orbiting Environmental Satellite; SAR – Synthetic Aperture Radar; SST – Sea Surface Temperature; STAR – Center for Satellite Applications and Research; TOPEX – Topographic Experiment University of Colorado (http://argo.colorado.edu/~realtime/gsfc_global-real-time_ssh/).

merging satellite, *in situ*, and flight planning information was a project-specific implementation of the Environmental Analysis System (EASy). EASy is a PC and server-based geographic information system (GIS) developed specifically for four-dimensional ocean applications (http://www.runeasy.com/) with built-in web-based functionality. It was used to store, integrate and visualize satellite, aircraft, buoy, and static (i.e., bathymetry and coastline) project data. Data stored on a parent sever was provided to the project participants via the built-in web-based GIS client, that included tools to collaboratively view and replay information by date and time, mark-up and bookmark the information displayed on screen. These features allowed EASy to be used as a communications tool during teleconferences for the purposes of sharing information over the web between project participants and to review possible areas of interest based on satellite data and drifting buoy movement.

2.3. Satellite remote sensing data

Based on the historical descriptions of marine debris distribution, on knowledge of the physical oceanography of the GoA, and especially on the advice of experts with knowledge of the regional ocean circulation (Stabeno, 2003; Ingraham, 2003), it was determined that the project should focus on frontal regions, eddies, coastal areas, and waters surrounding islands within the Alaska Coastal Current and Alaska Stream as likely areas of concentrated marine debris. Routine satellite data from a number of sources were then collected (see Table 2). For the most part, individual satellite images were consulted to observe features. Since this region has persistent cloud cover, many images had to be analyzed to find a few observations. In subsequent field programs, it was found that temporal composite images are most useful for feature detection in cloudy regions, but during 2003 this compositing capability had not been implemented yet.

Many types of satellite remote sensing data are useful for locating eddies, since oceanic eddies often have color, temperature, surface topography, and wave characteristics distinct from their surroundings. Altimeter sea surface height anomaly observations were found to be the most useful for tracking the larger eddies in the GoA. Altimeters penetrate clouds and thus one could see the eddy topography signature along the satellite nadir track every time an altimeter satellite passed overhead. Satellites carrying altimeters in 2003 were TOPEX/Poseidon, the first of the Jason satellites, and Geosat Follow On (GFO). We relied on sea surface height (SSH) anomaly composites which were constructed daily using altimeter tracks from the previous 10 days (TOPEX-Poseidon and Jason) and 35 days (GFO). Fig. 3 is an example of these composites produced using the Near Real-Time Altimetry web site of the University of Colorado – Colorado Center for Astrodynamics Research (Univ. of Colorado, 2003). In this figure, three eddies are identified from their distinctive sea surface height anomaly structure (height anomalies are areas of the ocean which are higher or lower than the surrounding mean sea level). These eddies were tracked in successive altimeter composites and observed also with infrared, ocean color, and SAR imagery. During 2003, the GhostNet project identified and tracked six eddies in the GoA. All were anticyclonic (i.e., with clockwise circulation) eddies with positive sea-surface-height anomalies. By the time of the flights in August

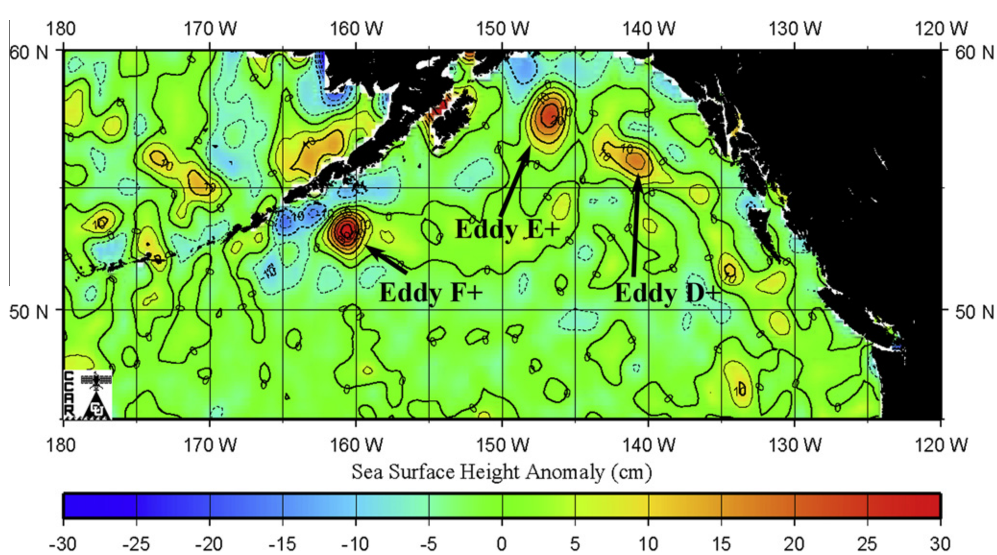

Fig. 3. Near real-time sea surface height (SSH) anomaly map for the Gulf of Alaska, August 1, 2003, derived from multi-day composites of satellite altimeter data. Shown are three large anti-cyclonic eddies designated D+, E+, and F+. The letter designations for the eddies are arbitrary ("+" means they were positive SSH anomalies). (Figure Courtesy of the University of Colorado–Colorado Center for Astrodynamics Research).

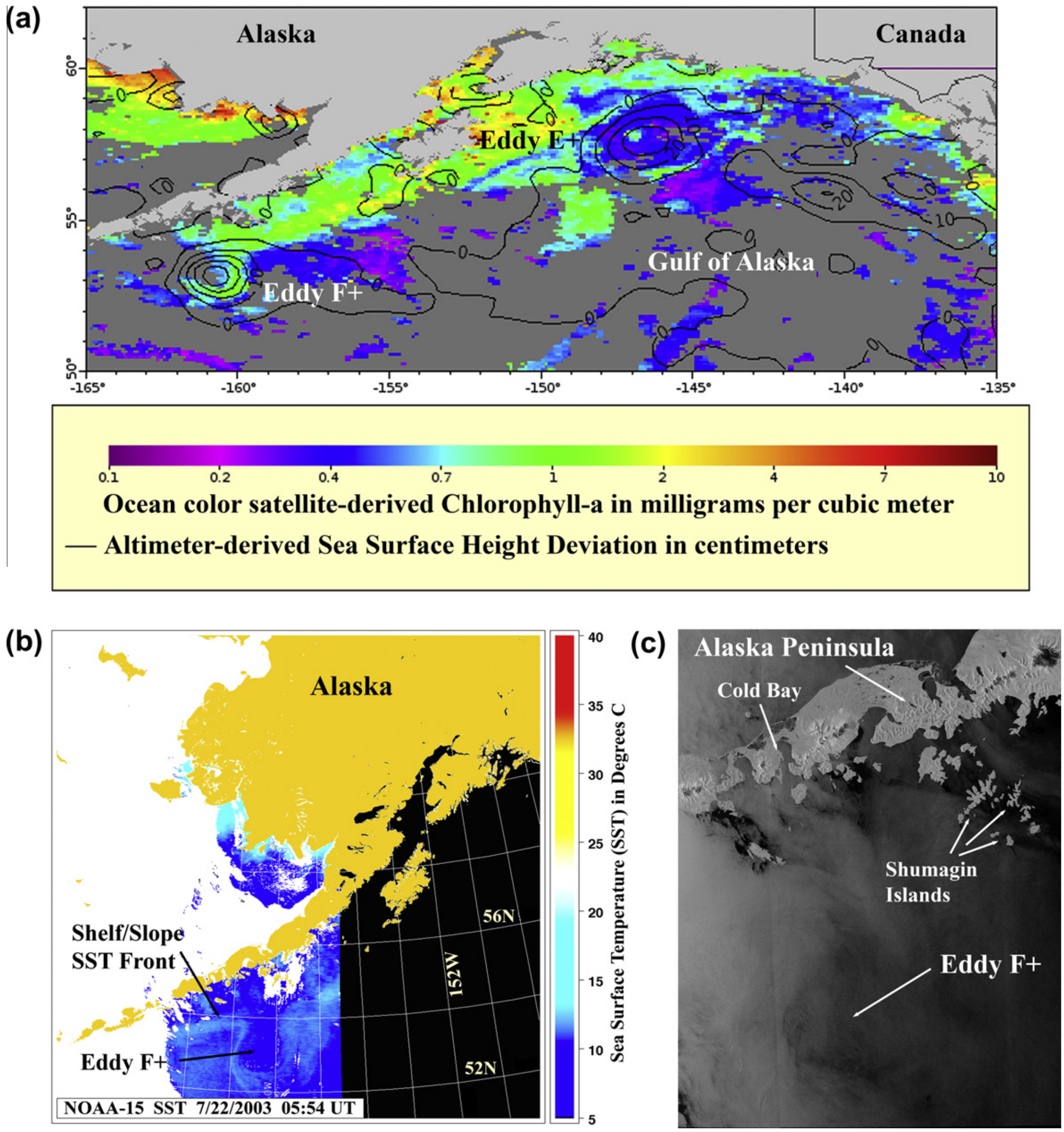

Fig. 4. Examples of eddies in satellite data. (a) Ocean chlorophyll 8-day composite in mg/m^3 for the period 7/28/2003–8/4/2003 derived from the SeaWiFS instrument on the Orbview-2 satellite mapped to 0.1 degrees of latitude and longitude (data courtesy of the NASA Goddard Space Flight Center, Distributed Active Archive Center, GeoEye, and NOAA CoastWatch). Contour overlay is altimeter-derived Sea Surface Height (SSH) Deviation from AVISO (science quality) (http://www.aviso.oceanobs.com/en/home/index.html) for 7/30/2003 mapped to 0.25 degrees (data courtesy of AVISO). SSH Deviation is contoured every 10 cm. Eddy E+ and F+ are evident as a pattern in the chlorophyll field. (b) NOAA-15 Polar Orbiting Environmental Satellite (POES) sea surface temperature (SST) image for July 22, 2003 at 05:54:02 UT. Eddy F+ is outlined by warmer Alaska Stream water wrapping around the eddy. The northern edge of the Alaska Stream forms a subtle SST front along the shelf break. (c) RADARSAT-1 Synthetic Aperture Radar (SAR) backscatter image from July 31, 2003, 04:28 UT, showing Eddy F+ as an area of somewhat decreased backscatter (the brighter the image the greater the backscatter). Image copyright Canadian Space Agency, 2003.

2003, only three of the six original eddies were still evident in the altimeter data (i.e., those shown in Fig. 3). These were arbitrarily designated as D+, E+, and F+ (with " + " meaning a positive SSH anomaly). The slow movement of these eddies was followed with the altimeter composites and then the exact position was pinpointed with IR sea surface temperature (SST) or chlorophyll imagery under clear-sky conditions, or with SAR imagery when coverage could be obtained and when wind conditions allowed observation of ocean features.

See Fig. 4 for an example of how these eddies appeared in the various types of satellite data. During the GoA survey flight planning, infrared SST and ocean chlorophyll imagery were analyzed for gradients and features by enhancing the imagery and looking for subtle changes. In most cases, relative SST and chlorophyll values were employed, not absolute values. The center and approximate radius of the eddies were determined from the remote sensing data and provided as flight guidance (in the form of "way points" giving the positions of end points of each straight line portion of a flight track) the day before each leg of the GhostNet flight. Thus, the satellite remote sensing imagery and the information derived from them on likely areas of convergence and concentration of floating debris formed the link between model predictions, buoy observations, and the flight survey.

2.4. Aircraft sensors

A King Air 90 aircraft was used for the GhostNet GoA flights. A single pilot flew the plane at an observing altitude of 305 m.

Table 3
Debris observation flight legs for the GhostNet Gulf of Alaska marine debris survey – July/August 2003.

Leg	Date (2003)	Flight track	Comments
1	7/20	Astoria OR – Port Hardy, Canada	Observed Columbia River plume
2	7/21	Port Hardy - Ketchikan, AK	Flew over small eddy obscured by fog
3	7/22	Ketchikan – Yakutat, AK	Flew over position of Eddy D + which was no longer visible
4	7/23	Yakutat – Kodiak, AK	Flew around Kayak Island
5	7/30	Kodiak – Cold Bay, AK	Observed shelf break front
6	7/30	Cold Bay – Cold Bay	Observed Eddy F+
7	7/31	Cold Bay – Kodiak	Coastal observations
8	8/01	Kodiak – Sitka, AK – Ketchikan	Observed Eddy E + and debris along shelf break
9	8/02	Ketchikan – Seattle, WA	Many coastal debris observations in Hecate Strait

Reasonable near-shore survey time resulted from the aircraft's 5.5 h fuel range. There were two equipment operators in the main cabin and an observer up front. The operator stations had two computer racks. The aircraft carried a sensor package that included: (1) A green-laser (532 nm) imaging Light Detection and Ranging (LIDAR) instrument as described by Churnside and Wilson (2004), which produced a narrow swath (5 m) but with a very high resolution (1 cm) at the surface. (2) A visible red–green–blue (RGB) video camera (Hitachi HV-D30 3CCD), which was able to image a surface swath of 186 m at the survey altitude of 305 m. National Television System Committee (NTSC) analog video (30 frames per second) was digitized and recorded on a JVC BR-DV600UA Mini digital video (DV) recorder. (3) An infrared (IR) imager (Raytheon Control*IR* 2000 B) imaged a swath width of 40 m on the water's surface at the survey altitude of 305 m. NTSC video (30 frames per second) from this IR imager was digitized and recorded on a JVC BR-DV600UA Mini DV recorder. (4) A calibrated infrared radiometer (Heitronics KT 15.85D) provided SST measurements along the flight track. The optics package was installed over a single large camera port in the rear of the cabin. In order to image the same water surface, all optics were co-located and bore-sighted.

The data from the imaging LIDAR, as well as the RGB and IR cameras were fed directly into the computer and analyzed by a software program written to provide near-real-time detection of anomalies in the water. For each of the five channels (LIDAR, R, G, B, and IR), a frame was considered to contain an anomaly if more than a specified number of pixels were above a specified threshold. The same was done for the ratio of the red channel to the blue channel, which was calculated for each pixel of each frame. Thresholds for pixel number and brightness were adjusted during the flight to maintain an acceptable false alarm rate. Generally, the pixel number was adjusted to match the size of features seen in the video (typically a few m^2) and then the threshold was adjusted until the system was producing detections at average rates of no more than one every few seconds. The threshold level produced by this technique varied from a few percent to almost 100% of the maximum value of each image. The software would alert the operator of a possible anomaly. It would also mark any anomalies detected in the digital video camera data with a Global Positioning System (GPS)-derived position and save the data from all three imagers for archival purposes and immediate operator review. The beta version of this software was tested during the flight. It was not yet considered operational, but experience was gained with the system, which was valuable for future improvement in anomaly detection techniques.

3. Results

The survey flights began on July 20, 2003 and ended August 2, 2003. The nine flight legs are listed in Table 3 and illustrated in Fig. 5. A summary of all the objects and wildlife spotted on each flight leg is given in Table 4, and a map of the location of the debris of anthropogenic and terrestrial origin is given in Fig. 6. A total of 102 objects of anthropogenic or terrestrial origin were recorded along with 142 observations of wildlife, kelp, and algal mats.

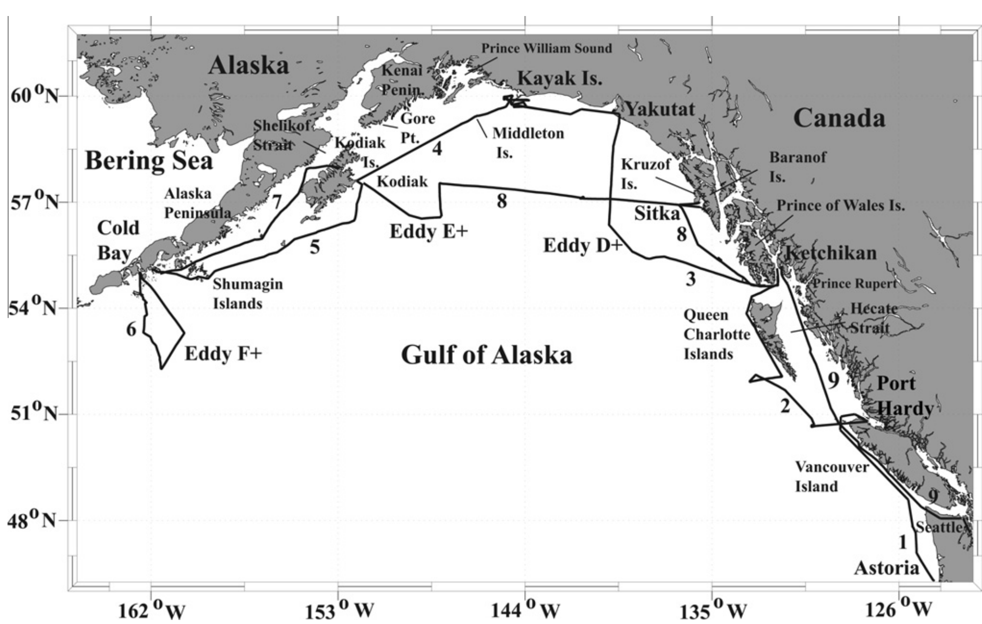

Fig. 5. GhostNet Gulf of Alaska field program flight tracks. Flight legs for the survey are numbered. Leg 1 was flown on July 20, 2003, beginning in Astoria Oregon and Leg 9 ended in Seattle on August 2, 2003. These legs were flown with a King Air 90 aircraft with a single pilot, two equipment operators, and an observer. An observing altitude of 305 m was maintained. Leg 3 targeted Eddy D+; Leg 4 observed Kayak Island; Leg 5 was along the shelf break; Leg 6 observed Eddy F+; Leg 7 was along the Alaska Peninsula and through Shelikof Strait; Leg 8 flew over Eddy E+ and along the shelf break in Southeast Alaska; and Leg 9 observed Hecate Strait.

Table 4
Marine debris and other objects/sea life observed during each leg of the GhostNet Gulf of Alaska marine debris survey – July/August 2003.[c]

Leg	Boards/logs/ trees	Fishing line/corks/ floats	General Debris (not identified)	Buoys	Fish Nets	Styro-foam	Kelp/Kelp Rafts	Whales	Algal Mats	Birds	Jelly-fish swarm
1											
2			1								
3											
4	4		12				4				
5			15	1			9	12		3	
6			1	1			13	14			
7	2						19	7			
8	10		9	2		1	13			1	1
9	16	19	4	1	3		39	4	3		
Total	32	19	42	5	3	1	97	37	3	4	1

[c] Total number of objects of anthropogenic or terrestrial origin: 102. Total objects of oceanic origin: 142.

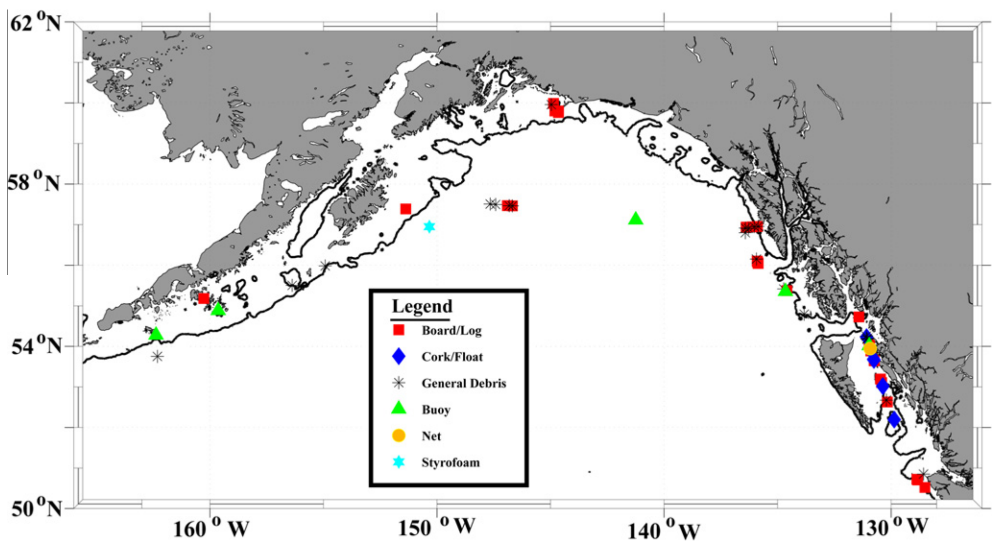

Fig. 6. Location of all anthropogenic debris and debris of terrestrial origin observed during the Gulf of Alaska Field Program, recorded by debris type. The isobath included on the map is for 200 m, showing the approximate position of the shelf/slope break. A total of 102 objects of anthropogenic or terrestrial origin were recorded, along with 142 observations of wildlife, kelp, and algal mats (not depicted on this figure). General debris (i.e., debris obviously anthropogenic, but unidentified) was the most common type, followed by logs/boards/trees, with fishing debris third.

Usually when the number of debris pieces in a grouping of debris was less than 10, the actual number was recorded by the observer. Sometimes debris counts were recorded as "a few" which is interpreted herein as 2; a plural designation, such as "floats," is interpreted as 3; and a designation of "many" has been recorded as 12. As Table 4 shows, the category of debris most observed was designated as "general debris" which is debris that was obviously of anthropogenic origin such as plastic debris, litter, or garbage, but was not readily identifiable. The second most common observation was that of logs, boards, or trees, followed by fishing debris. For objects obviously of oceanic origin, kelp and rafts of kelp were the most common. Observations of whales were the second most common oceanic object/sea life spotted.

The survey began at Astoria, Oregon. The first leg (July 20), which ended at Port Hardy, Canada (on the northern shore of Vancouver Island), was not a debris observation flight; however, the Columbia River plume was observed on the way. The second leg (7/21) targeted a small cyclonic eddy off the Vancouver coast (50.64°N, 129.94°W) which was observed in ocean color, SST, and SAR data. Unfortunately, the region of the eddy was covered with fog and no observations were possible. Only one piece of unidentified debris was sighted near the northern tip of Vancouver Island on the way to Ketchikan, Alaska. The third leg (7/22) from Ketchikan to Yakutat, Alaska targeted the position of an eddy (Sitka Eddy D+, with center located at 57°N, 141°W) which had been observed 5 days earlier in altimeter data as a positive sea surface height anomaly and in ocean color data as an anomalous chlorophyll feature (swirl). No debris was observed during the entire leg and there was no visual trace of the eddy, despite a flight track which took the King Air right over the eddy. For the fourth leg (7/23) from Yakutat to Kodiak, Alaska, the main target was Kayak Island, which stretches northeast to southwest in the Alaska Coastal Current (see Fig. 5) and from beach surveys (Johnson, 1990; King, 2008) is known to collect debris on its southeast shore (see Fig. 2a). An eddy-like structure had been observed in AVHRR SST data on July 19 to the west and north of Kayak Island. On this leg, four logs, 12 pieces of unidentified debris and 4 kelp rafts were observed. The logs were observed north and west of the island in the area of the eddy-like feature seen in the AVHRR data, at approximately 59.9°N, 144.9°W. Fig. 7 contains a LIDAR image of one of these logs as well as an example of a RGB and IR image of a similar-size log (the RGB and IR images of the same log as the LIDAR image are of insufficient quality for publication). Although the LIDAR field of view is much narrower than that of the RGB camera, the LIDAR's higher resolution allows less ambiguous debris identification. Fig. 8 shows an RGB frame of unidentified debris west of Kayak Island and an enhancement of this image using the red/blue ratio anomaly algorithm which defines an anomaly as having a red/blue ratio equal to or greater than 1.1. The fifth leg (7/30) occurred a week after the fourth leg, delayed by poor weather. This leg stretched

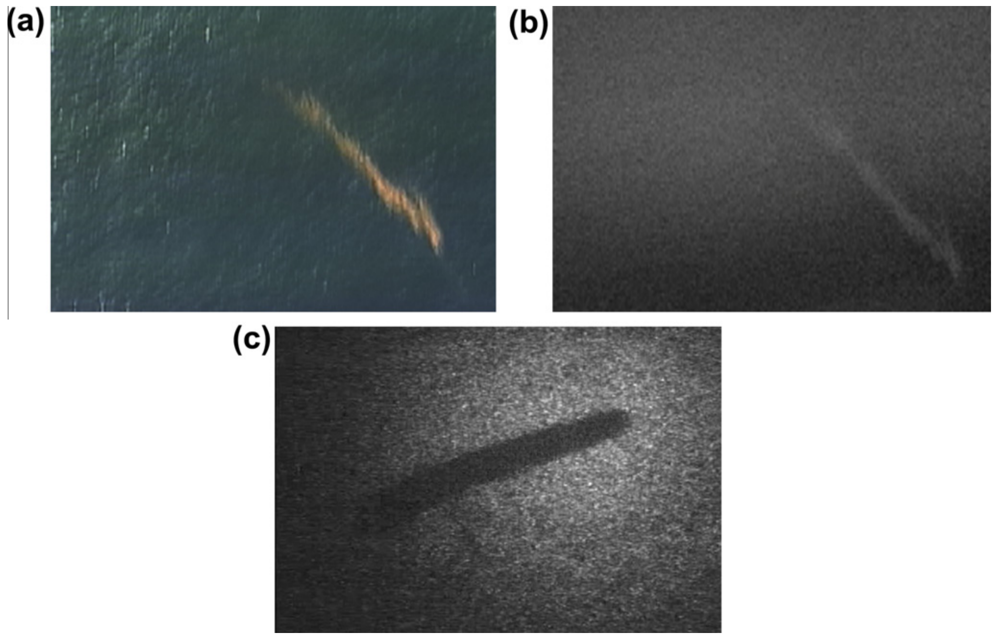

Fig. 7. Examples of images taken from the aircraft sensors used in the Gulf of Alaska Survey. (a) Visible red, green, blue (RGB) digital video image of a log taken on a pre-survey test flight. (b) Infrared (IR) image of the same log as (a). (c) LIDAR image of a similar log, but not the same log as (a and b). This log was observed west of Kayak Island during Leg 4 of the Gulf of Alaska Survey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

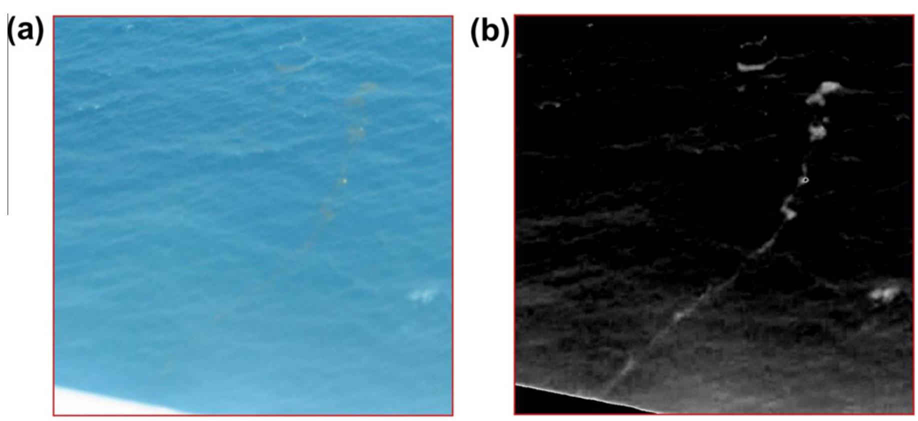

Fig. 8. Unidentified general debris observed on Leg 4 of the Gulf of Alaska survey, west of Kayak Island. (a) Visible red, green, blue (RGB) digital video image of the debris which may be a submerged fishing line with small floats. (b) Enhancement of the debris in (a) using a red/blue ratio anomaly algorithm (anomaly is defined as a red/blue ratio equal to or greater than 1.1).

from Kodiak to Cold Bay, Alaska, near the end of the Alaska Peninsula. The flight track was offshore along the shelf break where fronts had been seen in the AVHRR data (see Fig. 4b). On this leg, a streak of debris (recorded as 12 pieces) of general debris was observed as well as an orange buoy (54.88°N, 159.64°W). At least 12 whales, 9 kelp rafts and 3 birds were also observed. The sixth leg (7/30) left and returned to Cold Bay, targeting a persistent eddy (F+) south of the Alaska Peninsula. This positive sea surface anomaly had been seen in SAR imagery, MODIS chlorophyll imagery and AVHRR SST imagery in addition to the altimeter SSH anomaly maps (see Figs. 3 and 4). Only one buoy was observed (54.28°N, 162.37°W) near the shelf/slope break and one piece of general debris on the outer edge of the eddy, along with 14 whales and 13 kelp rafts. Three slicks were observed within Eddy F+, but only the one piece of debris. The position of Eddy F+ obtained from the remote sensing data and used to set the flight plan was out of date and the center of the eddy was missed. Only the outer perimeter of Eddy F+ was observed, and perhaps that is the reason that there were so few debris observations within Eddy F+. At this point in the field program, a flight to the Pribilof Islands was planned, but the weather was not good over the Bering Sea. The seventh leg (7/31) was from Cold Bay back to Kodiak, flying along the southeastern shore of the Alaska Peninsula through Shelikof Strait to Kodiak. Only 2 logs were spotted (in the vicinity of the Shumagin Islands) along with 7 whales and 19 kelp rafts.

The eighth leg (8/1) from Kodiak to Sitka, Alaska, crossed over the middle of Eddy E+ (57.6°N, 146.6°W), with a flight track crossing the open GoA to determine if debris could be found away from the coast. Eddy E+ was an anticyclonic Yakutat eddy with a positive sea surface height anomaly, a higher SST than the surrounding water and a signature in surface chlorophyll concentration (see Fig. 4a). Fig. 9 shows the flight track as well as the location of debris observations on a sea surface height anomaly map for August 1, 2009, the day of the overflight. White circles are objects of oceanic origin, while black circles are debris and objects of terrestrial origin. A good quantity of debris was spotted on this leg. A log was observed on the continental shelf near Kodiak Island and a piece of Styrofoam was observed seaward off the shelf break to the east.

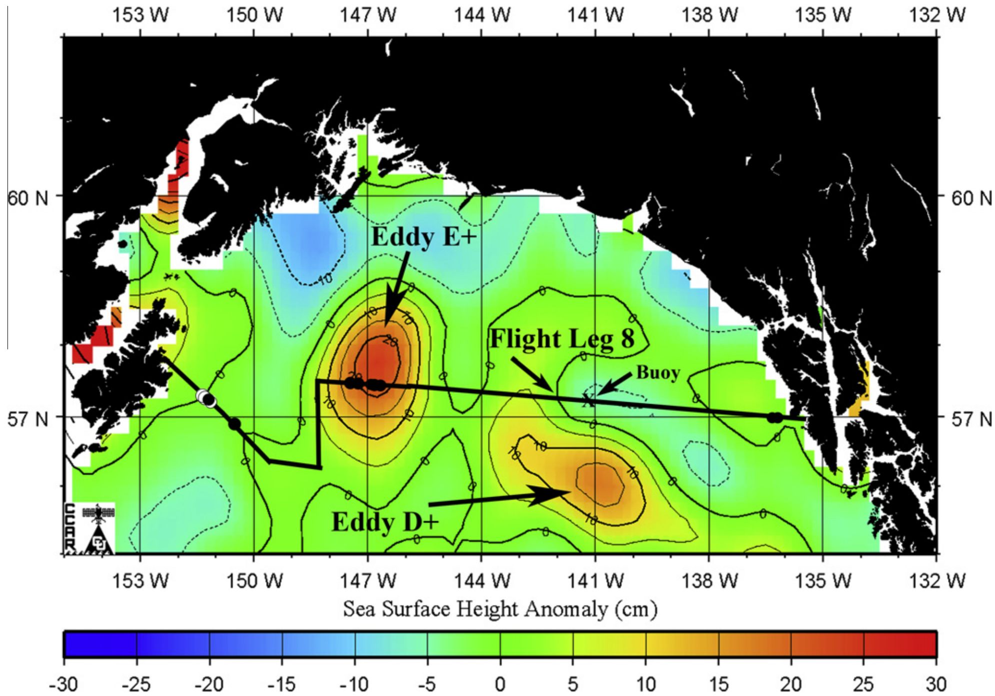

Fig. 9. Flight track for Leg 8 (August 1) of the GhostNet survey of the Gulf of Alaska. The flight track is shown along with the location of anthropogenic/terrestrial debris marked with black circles and objects of oceanic origin (i.e., kelp, birds, whales) marked with white circles. The flight track is superimposed on a sea surface height (SSH) anomaly map derived from altimeter data (composite period ending August 1, 2003). The locations of two eddies are given. Eddy E+, a positive sea surface height anomaly, was overflown on this leg. The "X" marks a buoy flown over on purpose. Debris were observed near Kodiak Island, within Eddy E+, and close to Baranof Island (Sea surface height anomaly product courtesy of University of Colorado, Colorado Center for Astrodynamics Research).

Table 5
Type of ocean region in which marine debris was observed during the GhostNet Gulf of Alaska marine debris survey – July/August 2003.

Type of ocean region	Boards/logs/trees	Fishing line/corks/floats	General debris (not identified)	Buoys	Fish nets	Styrofoam	Total by ocean region	Percent of total observations
Shelf	4		2	1			**7**	6.86
Shelf/Slope Break	7		18	2			27	26.47
Eddy	2 – E+		4 – E+, 1 – F+				6 – E+, 1 F+	6.86
Strait	12-Hecate	19- Hecate	4-Hecate	1-Hecate	3-Hecate		39-Hecate	38.24
Near Island	2-Shumagin Islands, 4-Kayak Is., 1-Kruzof Is.		12-Kayak Is. 1-Kruzof Is.				16-Kayak Is., 2-Shumagin Islands, 2 Kruzof Is.	19.61
Deep ocean				1		1	2	1.96
Total	32	19	42	5	3	1	102	100

Within Eddy E+ (which was located in deep water east of Kodiak Island and south of Prince William Sound at approximately 57.6°N, 146.6°W) were observed: "debris, brown debris, log, light brown debris, and log with garbage." A satellite-tracked buoy was purposely flown over at 57.12°N, 141.25°W. This was one of the buoys used to determine drift patterns in the GoA. Debris was again evident (small red debris and small white debris) as the aircraft approached Baranof Island and the airport at Sitka. After refueling at Sitka, Leg 8 continued on the seaward side of Baranof Island and Prince of Wales Island to Ketchikan (this part of the leg is not shown on Fig. 9) with additional coastal and shelf break observations of 7 logs/boards, 4 observations of general debris, and one buoy. Also observed were 13 kelp rafts, 1 bird, and a swarm of jellyfish. The ninth and final leg (8/2) had the most debris observations. This leg stretched from Ketchikan through the Hecate Strait east of the Queen Charlotte Islands, along the western coast of Vancouver Island, and then onto Seattle. The most debris was found in Hecate Strait. Observations included 16 logs/boards/trees, 19 floats/corks, 4 general debris objects, 1 buoy, and 3 fish nets. Objects of oceanic origin included 29 kelp rafts, 4 whales, and 3 algal mats, including one over 1.6 km in length.

Table 5 summarizes the type of ocean region in which each piee of anthropogenic and terrestrial debris was observed. Of all the debris of anthropogenic and terrestrial origin, 38.24% of the debris observations were made in Hecate Strait; 26.47% were in the vicinity of the shelf break, 19.61% were made close to islands, in particular Kayak Island, 6.86% on the continental shelf, and 6.86% in Eddy E+. In deep water of the open GoA, there were only two debris observations (1.96%).

4. Discussion

Debris was found primarily in coastal areas (particularly in Hecate Strait), near the shelf/slope break, behind Kayak Island, and in

Eddy E+. In two flights over the open GoA (Legs 3 and 8), only one piece of debris and one operating buoy were found in the open Gulf (except for debris within Eddy E+). In particular, for Leg 8, observers searched for debris during the entire flight from Kodiak to Sitka and, with only two exceptions, debris was only found (1) in the vicinity of Kodiak Island, (2) within Eddy E+, and (3) along the coast of Baranof Island in Southeast Alaska. The exceptions were a piece of Styrofoam observed at 56.9°N, 150.3°W and a satellite-tracked buoy observed at 57.12°N, 141.25°W. This indicates that debris is concentrated near the shore of the GoA within the Alaska Coastal Current, rather than in the deep water of the open Gulf – with the exception of debris found in long-lived eddies, or at least in one of these eddies. Admittedly, however, an exhaustive grid of the open Gulf was not flown to fully verify this indication.

Eddy E+ was studied and sampled in May and September of 2003 (Ladd et al., 2005a); i.e., both before and after the GhostNet GoA survey. This Yakutat eddy was formed during the winter of 2003 near Yakutat, Alaska and moved along the shelf break of the northern GoA. In May, the eddy core (located approximately between 100 and 200 m depth at the center of the eddy) was found on average to be warmer (by 0.8 °C), less saline (by ~0.3 psu), and higher in nitrate (by 5.9 μM) than surrounding waters of the GoA basin – similar in properties to shelf waters near Yakutat. The mixed-layer depth within the eddy was approximately 35 m. One drifter, released in the eddy in May and drogued at 40 m, was still circling the eddy in September. During its time within the eddy, it circled at a mean azimuthal speed of approximately 10 cm/s. The eddy translated approximately 136 km between May and September at an average speed of 1 km/day (Ladd et al., 2005a). Since eddies like E+ remain close to the shelf break, and interact with the Alaska Current/Stream, they can pull shelf water offshore, resulting in cross-shelf exchange (Ladd et al., 2005b). Fig. 4a shows the warmer waters of the Alaska Stream wrapping around Eddy F+. It is postulated that debris may be entrained from shelf water when these eddies form or from shelf break water that is pulled around the eddy as it circulates and translates.

Leg 9 had the most debris observations (including about 40% of all of the anthropogenic or terrestrial debris observations and all of the fishing-related debris observations), mostly observed in Hecate Strait within Canadian shelf waters. This is an area close to population centers and with considerable waterborne activity including commercial and sport fishing; container, bulk cargo, and oil tanker traffic to and from the Port of Prince Rupert; cruise and ferry traffic; recreational boating and sailing; and wildlife tourism. During 2007, the Port of Prince Rupert was visited by 60 large cruise ships carrying a total of 100,000 passengers (Joseph and Gunton, 2009). All of this activity could account for the levels of debris found. In the protected waters of Hecate Strait, this debris would tend to stay in the area because there is less mixing with the open ocean than in other areas surveyed.

Almost all of the debris observations were made by visual observation. Some objects were captured on visible and IR video or by the LIDAR instrument, which helped in their identification. All instruments, however, had narrow observation swath widths, so were not able to sample as much ocean as one could by eye. The real advantage of the sensors over the human eye was in their ability to automatically record data; to process data with various algorithms; to not tire with time, and to automatically GPS/time stamp the data. For example, the red/blue ratio anomaly detector allowed better contrast between debris and water than was evident in normal RGB imagery (see Fig. 8). While each instrument added its own unique perspective to the detection of ocean surface anomalies, the visible (RGB) camera proved to be the most effective overall and would be the single choice if aircraft payload or budget was limited. The LIDAR package added significant complexity to the sensor package over the RGB or IR imagers. While all the sensor data was being recorded on digital tape, audio tracks were used to record GPS flight track data and aircraft intercom communications. The aircraft intercom conversations proved useful in post-flight review of the image data as they helped define what was being seen visually, record the reactions of the operators and tie the visual observations to features in the satellite imagery.

At the beginning of the Methods section of this paper is a list of seven activities which formed a strategy for the GhostNet survey in the GoA. Some of these activities worked well, some did not. The following is an assessment of each activity with notes on what was done differently in subsequent surveys as a result of lessons learned in the GoA pilot survey.

1. Obtain insight from historical surveys and use of drift models for survey planning: Historical drift model output served along with published information on GoA circulation and ocean features such as eddies to provide insight during the survey formulation phase. For survey planning just before each flight leg, drift model output was not used – rather satellite data and weather forecast model output were employed.

2. Study drifting buoy tracks including specially deployed GhostNet buoys to understand current patterns and areas of convergence: The GhostNet buoys were not fully operational prior to the GoA survey, and so did not play a part in the survey. Already-deployed drifters were tracked and provided some insight as to circulation patterns. There were not enough buoys to give any indication of convergence areas and no buoys were attached to nets. The tracks of some buoys indicated the presence of eddy features.

3. Develop GIS techniques for analysis of satellite, buoy, and meteorological data: The GIS environment used for the GoA survey was a customized version of the EASy 4D GIS system. EASy was used for integrating remote sensing and *in situ* data sets. Built-in software-based tools were utilized to import and visualize satellite imagery and time- and location-based buoy data. In instances where new satellite datasets were required, EASy was updated to add the ability to import and read the relevant image header files. EASy's web-based *NetViewer* GIS system was simple to configure and stand up on the server side, but was sensitive to security settings on the client side browsers accessing it (particularly early versions of Microsoft Internet Explorer). This required on-going support and training to ensure that team members could readily access and visualize project data. As a result, the web mapping components of EASy were systematically upgraded during the project to ensure a more robust performance. The strength of the software lies in its ability to allow trained users to quickly integrate a wide variety of remote sensing datasets, true 4D oceanographic data (i.e., current vectors or towed profiles) and real-time *in situ* information from the field. At the time, EASy did not contain tools to systematically analyze or query spatial patterns; this required users to manually search for features of interest within the oceanographic data. Post-project, the EASy system has continued to be actively developed and deployed on additional projects. For subsequent GhostNet surveys, all satellite and *in situ* data were converted to GeoTIFF or shapefiles since these formats can be readily ingested by most commercial image display and processing programs, freeing project participants to use the image processing and GIS software with which they are most familiar. Conversion of all satellite and ancillary data to common GIS formats has been found to be critical for flight planning and post-flight analysis.

4. Use satellite imagery to locate regions of convergence: Although persistent cloudiness in the GoA made it challenging to use visible and IR imagery to locate features, there were enough cloud-free opportunities to locate eddies, but only if the approximate positions were known from the altimeter SSH maps. The following are the lessons learned concerning satellite data: (a) Altimeter data are the most important remote sensing data for

mapping large long-lasting eddies. Since larger eddies are either positive or negative SSH anomalies, they show up well on altimeter SSH anomaly maps. The altimeter data are available regardless of cloud cover and illumination, providing daily updates on eddy locations. This was particularly important in Alaskan waters with its ubiquitous cloud cover. (b) Cloud detection techniques used with near-real-time MODIS data at the time of the flights were not accurate enough for calculation of weekly composites (this has been improved and weekly composites are now available from the West Coast CoastWatch website: http://coastwatch.pfel.noaa.gov/). (c) Single image chlorophyll and SST observations at full resolution are the most useful data for mapping eddies under cloud-free conditions. (d) SAR imagery is useful for mapping both small and large eddies under favorable wind conditions (between 3 and 12 m/s) when surfactants such as algae blooms dampen the capillary and small gravity waves and provide a trace of the ocean circulation as they are swept along with the eddy current.

5. Test and refine aircraft sensors and observation strategies: Through the use of test flights prior to the survey, the sensors were tested and adjusted. All sensors performed well but were not as useful in locating debris as in documenting the survey. The following were the lessons learned: (a) Visual observation by one or more trained observers is the most reliable method of detecting debris and observing the maximum amount of debris along the flight track. (b) Visible video and still images can be useful for marine debris detection and identification. The requirements of wide swath for detection and high resolution for identification may require multiple cameras. Image enhancement can reveal features not easily visible to the naked eye. Color processing is especially useful in this regard. (c) LIDAR imagery did not cover a big enough swath to be practical for marine debris surveys. A scanning LIDAR may provide a larger useful swath, but off-nadir viewing would require research and testing. A LIDAR that can be steered to possible features identified by passive imagery would help to reduce false detections created by passive imagery alone. (d) IR imagery provides limited useful data compared to RGB imagery; however, under certain environmental conditions that allow for a differential in temperature between the ocean surface and objects floating on the surface, IR sensors can be useful for debris identification. IR imagery can also be useful for indirect detection by helping to locate birds that may be drawn to floating debris. The IR sensor is equally effective during low light conditions. (e) Anomaly detection software is critical in order to accomplish a near-real-time analysis of the remote sensing data being collected. Further development of anomaly software is required before this technique can be used in an automated fashion without requiring manual threshold adjustments by the operator. Optimal thresholds varied rapidly as illumination and surface roughness changed. For example, the threshold settings had to be redone each time the aircraft turned, because this changed the relative solar azimuth angle. Feature tracking to establish persistence would help to distinguish between debris and surface reflections that change as the look angle changes. Computers in use for the 2003 survey were not quite fast enough for near-real-time anomaly detection. By the 2005 GhostNet survey, computers with sufficient speed were obtained.

6. Assess wind and wave conditions to select optimum flight track: Optimum observing conditions are critical to successful debris surveys. Prior to each flight, marine and aviation weather reports available via phone from the local airport and NOAA Weather Service offices as well as buoy reports of wind and wave data available through the Internet were consulted. The Gulf of Alaska does have coastal meteorological observations, as well as aviation and surface ship reports. These observations and forecasts were sufficient to determine whether wind and wave conditions were conducive to good debris observations. Subsequent GhostNet surveys relied more heavily on scatterometer wind measurements and meteorological/ocean forecast model output since these surveys were over the North Pacific where *in situ* observations are scarce. Weather did affect the ability to fly safely during one entire week in the middle of the GoA field program, causing the survey team to lay over in Kodiak, Alaska. Poor weather in the Bering Sea led to the abandonment of the flight leg planned to the Pribilof Islands. And fog prevented observation of a small eddy during Flight Leg 2. Weather conditions for all the other flight legs had wind and wave conditions within the parameters for good observing conditions.

7. Fly aircraft survey: During the survey, one observer was sufficient for the frequency of debris encountered, except in Hecate Strait where two observers would have been optimum to assure that nothing was missed. Lessons learned for future flights were: (a) At least two observers are best to observe both sides of the flight track beyond the swath of the imaging equipment. (b) A flight altitude of approximately 300 m is optimum for visual observation of debris with dimensions greater than about 10 cm. Human visual resolution is nominally a few mm at this range, so 10 cm objects can generally be identified. (c) Communication between the flight crew and the satellite image analysts on the ground was problematic. Direct communication during the flight would have been very useful (and was employed in the 2005 GhostNet flights). (d) It would have been useful to the flight crew to be able to look at the GPS position of the aircraft plotted on the satellite data. (e) An aircraft with a greater fuel range is necessary for surveys outside of near-shore areas (a NOAA P3 was used for subsequent GhostNet flights to the North Pacific Subtropical Convergence Zone).

Taking advantage of the lessons learned from the Gulf of Alaska Field Program, the GhostNet project conducted a second field program in the spring of 2005, this time to the North Pacific Subtropical Convergence Zone north of Hawaii. Substantial debris was located mostly by visual observation from a NOAA P3 aircraft flying at 300 m altitude. Individually logged were 1885 debris observations and 428 animal observations on one short test flight and three long (as much as 9 h) observation flights to the convergence zone (Pichel et al., 2007). A Debris Estimated Likelihood Index (DELI) was developed to attempt to predict the relative likelihood of finding debris north of Hawaii in spring using satellite ocean color and sea surface temperature data. More recently, in 2008, a prototype of the GhostNet Unmanned Aerial System (UAS) was tested from a small boat off of Hawaii and on a NOAA cruise to the North Pacific Subtropical Convergence Zone north of Hawaii (McElwee and Morishege, 2010). Current GhostNet activities are focused on completing development of this ship-launched UAS to enable low-cost surveys of the ocean with visible sensors, detecting nets as anomalies in the color of the water. The ship can then recover any debris sighted for eventual disposal and/or recycling.

5. Conclusions

During July and August 2003, a 14-day marine debris survey of the Gulf of Alaska was undertaken by the GhostNet project. This was the first GhostNet field program and served as a pilot for subsequent debris survey flights. Lessons learned during this pilot survey proved invaluable for planning and executing more extensive surveys of the North Pacific Subtropical Convergence Zone. Planning for the Gulf of Alaska survey utilized available historic debris surveys, drifting buoy tracks, ocean drift model analyses, and satellite remote sensing data. It was decided to concentrate on observing frontal areas such as the shelf break front, and eddies as likely areas for the concentration of marine debris in addition to near-shore and island surveillance. Information on the suggested flight track to observe the areas of likely convergence was provided to the flight crew the day prior to each flight leg. A total of 102 individual observations of debris of anthropogenic/terrestrial origin were logged in nine flight legs. In addition, 142 observations were made of kelp rafts, whales, algal mats, birds, and one jellyfish swarm. Almost 40% of the anthropogenic/terrestrial debris observations, including all the fishing-related debris observations were made on the final leg of the survey in Hecate Strait. Debris was observed along the shelf break, close to islands extending into the Alaska Coastal Current, on the continental shelf, and in one long-lived eddy, Eddy E+. Very little debris was observed during two flight legs in the open Gulf of Alaska, except in Eddy E+. Techniques for detection of possible convergent areas, techniques for observing marine debris, and lessons learned from the Gulf of Alaska survey were all refined and utilized with success in subsequent GhostNet field programs. These techniques are quite generally applicable for marine debris surveys in other ocean areas from the tropics to high latitudes.

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