ORNL/TM-13032

ENVIRONMENTAL EFFECTS OF THE U.S. ANTARCTIC PROGRAM'S USE OF BALLOONS IN ANTARCTICA

Lance N. McCold
Energy Division

Gerald K. Eddlemon
Environmental Sciences Division

Terrance J. Blasing
Energy Division

June 1995

Prepared for the
National Science Foundation
Office of Polar Programs

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ASA	Antarctic Support Associates
ft	foot
g	gram
GPS	global positioning system
h	hour
in.	inch
JACEE	Japanese/American Cosmic Ray Emulation Chamber Experiment
JARE	Japanese Antarctic Research Expedition
kg	kilogram
km	kilometer
lb	pound
LAMB	Long-Duration Antarctic Mars Calibration Balloon
LDHL	Long-Duration Heavy-Lift
m	meter
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NSBF	National Scientific Balloon Facility
NSF	National Science Foundation
NSFA	Naval Support Force, Antarctica
OPP	Office of Polar Programs
ORNL	Oak Ridge National Laboratory
oz	ounce
Protocol	Protocol on Environmental Protection to the Antarctic Treaty
S-116	A High-Resolution Gamma-Ray and Hard X-ray Spectrometer (HIREGS) for the MAX '91 Long Duration Balloon Facility (LDBF) Program
S-131	In-situ Measurement of Solar Stratospheric Clouds, Condensation Nuclei, and Ozone in the Springtime Antarctic Stratosphere
S-145	Long-Duration Ballooning - (LDB) Program
S-146	Joint U.S.-Russian Long Duration Antarctic Mars Calibration Balloon (LAMB) Mission
S-147	Antarctic Long-Duration Balloon Flights for the Japanese/American Cosmic-Ray Emulsion-Chamber Experiment (JACEE) Collaboration
S-257A	South Pole Monitoring for Climate Change
S-283	Antarctic Automatic Weather Stations
SPA	Specially Protected Areas
SSSI	Site of Special Scientific Interest
USAP	U.S. Antarctic Program
UV	ultraviolet

1. INTRODUCTION

Research activities and the associated support operations conducted by the U.S. Antarctic Program (USAP) in Antarctica require the periodic use of balloons. To support aircraft operations, for example, balloons are launched at 12-h intervals to determine weather conditions at different altitudes. Research balloons carry instruments to measure concentrations of contaminants in the troposphere or levels of ozone in the stratosphere and to make astrophysical observations. In its extensive support of the operations and research in Antarctica, the USAP—which is part of the National Science Foundation (NSF), Office of Polar Programs (OPP)—recognizes the potentially profound impacts that its activities could have on the continent. Accordingly, reducing human impacts on the Antarctic environment is a major goal of the USAP.

This report evaluates the potential environmental impacts of balloon use by the USAP and identifies possible mitigation measures. The purpose of this study is to provide background information upon which the USAP may draw when complying with its responsibilities under the National Environmental Policy Act of 1969 (NEPA), the Antarctic Treaty, and the Madrid Protocol (hereafter referred to as the Protocol).[1] These responsibilities are spelled out in the implementing regulations for NEPA (40 CFR 1500–1508), and in the provisions of the Protocol.

The use of balloons is generally perceived as innocuous and unlikely to adversely affect the environment. That judgement may be warranted for populated areas, but the physical and biological character of Antarctica is very different from most of the inhabited world. In addition, the international consensus on how Antarctica should be managed (as embodied in the Protocol) sets high standards for environmental protection. Article 2 of the Protocol designates Antarctica "a natural reserve, devoted to peace and science." Article 3 spells out "environmental principles" for protection of the antarctic environment:

1. The protection of the antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica, including its wilderness and aesthetic values and its value as an area for the conduct of scientific research, in particular research essential to understanding

[1]The Antarctic Treaty, currently accepted by 39 nations, provides that the continent of Antarctica will be used for peaceful purposes only. The Protocol on Environmental Protection to the Antarctic Treaty (called the Madrid Protocol) establishes the requirements for environmental impact assessment of proposed activities on the continent.

the global environment, shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area.

2. To this end:

   (a) activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the antarctic environment and dependent and associated ecosystems;

   (b) activities in the Antarctic Treaty area shall be planned and conducted so as to avoid:

      (i) adverse effects on climate or weather patterns;

      (ii) significant adverse effects on air or water quality;

      (iii) significant changes in the atmospheric, terrestrial (including aquatic), glacial, or marine environments;

      (iv) detrimental changes in the distribution, abundance, or productivity of species or populations of species of fauna and flora;

      (v) further jeopardy to endangered or threatened species or populations of such species; or

      (vi) degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic, or wilderness significance.

Given the pristine to nearly pristine state of most of Antarctica, these environmental principles mean that disturbances that would be considered negligible in most environments could be significant in Antarctica.

Annex II to the Protocol prohibits taking of or harmful interference with antarctic fauna and flora except in accordance with a permit. As explained below, there is the possibility that balloons or their payloads may adversely affect antarctic fauna or flora.

Annex III requires that most solid and hazardous wastes be disposed of by removing them from Antarctica. Among the items that must be removed, the Annex specifically mentions (among others) electrical batteries, polystyrene foam, rubber, and "all other plastic wastes" (except low-density polyethylene containers for storing waste that are subsequently incinerated). As described below, balloons are made of rubber or plastic, the payloads are usually enclosed in polystyrene boxes, and alkaline or lithium electrical batteries power all but a few special payloads.

2. CURRENT USES OF BALLOONS IN ANTARCTICA

2.1 USAP BALLOON OPERATIONS

The USAP uses balloons in Antarctica to conduct scientific research, to facilitate safe air transport, and to provide data for global weather predictions. Each year, the McMurdo and South Pole stations together launch over 1000 small balloons carrying rawinsondes[2] and over 100 medium-size balloons carrying ozonesondes for research on the stratosphere. In addition, two very large balloons are launched from McMurdo each year during December for astrophysical research purposes. Rawinsondes are launched daily at the McMurdo and South Pole stations to collect data for understanding global weather patterns by recording upper atmosphere wind patterns and by locating the transition between the troposphere and the stratosphere. During the austral summer, rawinsondes are launched twice per day to provide more detailed weather data in support of aircraft operations. These weather sondes also provide additional data to help understand global weather patterns.

Ozonesondes are launched to measure ozone concentrations in the stratosphere during the austral spring in support of research on stratospheric ozone depletion. In addition, some ozonesondes measure particle concentrations or moisture at various altitudes. Although instruments on satellites can determine total ozone column thickness over wide areas, they cannot provide the more specific data obtained by ozonesondes.

The USAP uses high-altitude, long-duration balloons for making astrophysical observations. These balloons fly for approximately 10–20 days at about 40 km (130,000 ft) above sea level, while making one or two circuits of the pole. Because these altitudes are above most of the atmosphere, the balloons can serve as platforms for observations that cannot be made from the earth's surface. Performing observations in Antarctica has the advantage that most points in the southern sky are within view 24 h/day, allowing unusually long periods of uninterrupted observations.

---

[2]Sondes are devices for measuring physical and meteorological conditions at high altitudes. A rawinsonde is a radio-sonde that is tracked by a radio direction-finding device to determine the velocity of winds aloft. An ozonesonde provides data that are used to determine ozone concentrations in the upper atmosphere.

2.1.1 Rawinsondes (Weather Balloons)

Rawinsondes flown by the USAP consist of 220-g (0.5-lb) instrument packages suspended beneath a helium-filled balloon. The instrument packages consist of expanded polystyrene boxes supporting a carbon hygristor for measuring relative humidity, a pressure transducer for measuring altitude, a thermistor for temperature measurements, a radio transmitter, an antenna, and two (transistor-battery size) 9-V batteries to power the sonde for about 2 hours. Generally, during very cold weather, sondes have been powered by lithium batteries, and alkaline batteries have been used during warmer periods. Current practice at McMurdo is to use lithium batteries to power rawinsondes; past practice was to use one or two alkaline batteries [Lt. Commander John Josephs, Naval Supply Force, Antarctic (NSFA), personal communication to G. K. Eddlemon, ORNL, September 21, 1994].

Two types of balloons are used to carry rawinsondes aloft (Table 1). The most commonly used balloon is a 650-g (1.3-lb), uncolored, neoprene balloon containing approximately 1.4 m^3 (50 ft^3) of helium. These balloons are relatively inexpensive (Sect. 5), but they become brittle at temperatures below −70°C (−94°F) and tend to burst at relatively low altitudes [less than 15 km (~49,000 ft)] when flown during very cold weather. The other balloon used for rawinsondes is a (200-m^3) 7500-ft^3 polyethylene balloon made of 0.25-mil-thick transparent plastic and weighing about 1.6 kg (3.5 lb). At launch they contain a little more helium than the neoprene balloons to counter balance their higher weight. These balloons can typically rise to more than 25 km (~82,000 ft) above sea level before bursting. (Polyethylene balloons are larger than neoprene balloons because neoprene balloons stretch significantly as they rise while polyethylene balloons stretch very little.)

About 500 rawinsondes are flown from the South Pole Station, and about 650 rawinsondes are flown from McMurdo Station each year. Most balloons are neoprene, but polyethylene balloons are used to supplement soundings by rubber balloons during the coldest part of the year. At the South Pole Station polyethylene balloons are flown from April through September. From July 1992 through June 1993, 82 polyethylene balloons with rawinsondes were flown from the South Pole Station. Fewer than 10 of the 650 weather balloons flown from McMurdo each year are polyethylene (Lt. Commander John Josephs, NSFA, personal communication to G. K. Eddlemon, ORNL, September 21, 1994).

No effort is made to recover either the balloons or the rawinsondes. The rawinsondes are inexpensive costing about $100 each. Recovering them would be costly and dangerous during favorable weather, and impossible during unfavorable weather. Tracking the descending balloons is generally not possible because they often lose power about the time they burst, drop from view, and/or their signals have become too weak because of distance and obstructions. In the McMurdo area, balloons and payloads are estimated to land as much as 200 km (120 nautical miles) from McMurdo (Section 3, Figure 3).

Rawinsondes have also been flown from several other U.S. stations and camps including Byrd Surface Camp, Ellsworth, Wilkes, Hallett, Little Rockford, and others. There are no good records of the numbers of launches from these sites. Rawinsondes are launched only from McMurdo and South Pole Stations at present.

2.1.2 Ozonesondes

Ozonesondes consist of an ozone pump, a radiosonde, and in some cases other special instruments. The ozone pump is enclosed in a 0.19 × 0.19 × 0.25 m (7.5 × 7.5 × 10 in.) polystyrene foam box. The pump draws air through a chamber containing 4.5 ml (0.2 oz) of a 1% potassium iodide solution used to measure the concentration of ozone in the air. The ozone pump produces an electronic signal that is broadcast by the radiosonde and is powered by a small 6-cell lithium battery. The radiosonde is powered by seven small lithium battery cells that provide 21 V. It is strapped to the outside of the ozone pump with tape.

About a dozen larger ozonesondes are launched from McMurdo each year. In addition to the ozone pump described above, these ozonesondes include two photomultiplier tubes for measuring the concentration of particles, a pressure/temperature transducer and a global positioning system receiver to aid recovery of the instruments. These sondes are enclosed in a polystyrene foam box that measures approximately 0.3 × 0.3 × 0.75 m (1 × 1 × 2.5 ft). These packages use 4 large lithium cells that are about the diameter of a D-cell but approximately twice the length of a standard D-cell, a small 6-cell lithium battery to power the ozone pump, and 7 AA-sized alkaline cells.

Ozonesondes are flown from McMurdo, the South Pole, and Palmer Stations (Table 1). About 75 ozonesondes are launched from the South Pole Station each year. They are launched

Table 1. Characteristics of balloons used by the U.S. Antarctic Program

Balloon use	Payload weight	Balloon		Number of launches per year
		Size	Material	
		McMurdo Station		
Rawinsonde	220 g	650 g	neoprene	~650
	220 g	200 m^3 2.6 kg	0.25-mil polyethylene	~10
Ononesondes				
Ozone detector	620 g	500 m^3 2.8 kg	0.25-mil polyethylene	25–30
Ozone and particle detectors		1500 m^3 4.8 kg	0.25-mil polyethylene	9–12
Ozone and condensation nuclei detectors		4000 m^3 8.2 kg	0.25-mil polyethylene	3
Long-duration, high-altitude	$\leq$2,000 kg	800,000 m^3 1,600 kg	0.8-mil polyethylene	2
Pathfinders	9.1 kg	7000 m^3 17 kg	0.25-mil polyethylene	2-5
Pilot	220 g	650 g	neoprene	2-5
		South Pole Station		
Rawinsonde	220 g	650 g	neoprene	~400
	220 g	200 m^3 2.6 kg	0.25-mil polyethylene	~100
Ozonesonde				
Ozone detector	620 g	500 m^3 2.8 kg	0.25-mil polyethylene	70–80
Ozone and water-vapor detectors		500 m^3 2.8 kg	0.25-mil polyethylene	0-6
		Palmer Station		
Ozonesonde	0.5 kg[a]	<1 kg[a]	neoprene	~25[a]

[a]The payloads consist of a rawinsonde and ozonesonde weighing 0.5 kg. (These are probably the same combinations of ozonesonde and rawinsonde with an actual weight of 620 g.) The balloons described as less than 1 kg are probably 1 kg neoprene balloons because the 650-g neoprene balloons are probably not large enough to lift the 420-g payload to the desired altitude. Approximately 50 ozonesondes are launched every other year (Arnold Torres, Wallops Flight Facility, Goddard Space Flight Center, Wallops Island, Virginia, personal communication to G. K. Eddlemon, ORNL, September 24, 1994).

every 3 days during August through November, and once per week during the remainder of the year. These balloons are carried to altitudes between 25 and 30 km (80,000 and 100,000 ft) by 500-m^3 (19,000-ft^3) polyethylene balloons weighing 3.5–4 kg (8–9 lb).

Ozonesondes are flown from McMurdo during August, September, and October. Twenty-five to 30 small ozonesondes are carried to altitudes of 25–30 km (80,000–100,000 ft) (Table 1). The 500-m^3 (19,000-ft^3) polyethylene balloons are used in August and September before the stratosphere warms. Rubber balloons weighing about 1.5 kg (3 lb) may be used later in the season (after about October 15) when the stratosphere becomes warmer than −70°C (−94°F).

About 12 larger ozonesondes with particle detectors are launched per year from McMurdo. Nine are carried to an altitude of 30–35 km (100,000–115,000 ft) by 1,500-m^3 (54,000-ft^3) plastic balloons weighing 7–9 kg (15–20 lb). Three ozonesonde/particle detector packages are carried to an altitude of 36–37 km (118,000–121,000 ft) by 4000-m^3 (141,000-ft^3) balloons to look for condensation nuclei at higher altitudes. A timer on the balloons that lift the ozonesonde/particle detector packages detonates a small explosive that bursts and separates the balloon from the payload. The payload descends under a 3–3.5-m (10–12-ft) diameter parachute. On contact with the ground, the parachute separates from the payload. These larger ozonesonde/particle detector payloads also carry global positioning systems to aid in their recovery. During 1992, 9 of the 12 ozonesondes with particle detectors launched from McMurdo were recovered, 2 went into the ocean, and 1 could not be found (Table 2). The balloons are almost never recovered, and the parachutes are recovered only if they are found near the payload. No attempt is made to recover either balloons or ozonesondes launched from the South Pole Station.

Approximately 50 ozonesondes are launched from Palmer Station every other year. These are similar to the ozonesondes flown from McMurdo except that only neoprene balloons are flown from Palmer Station.

2.1.3 Long-Duration, High-Altitude Balloons

Two long-duration, high-altitude balloon flights are made each year from McMurdo. The balloons, which fly at about 40 km (130,000 ft), make a circuit around the pole in about 10 days. The balloons are believed to be capable of staying aloft for 21 days to make two circuits of the pole before being brought down near McMurdo.

Table 2. Landing sites and fates of high-value ozonesondes launched from McMurdo Station in 1992[a]

Launch date	Landing site: Latitude	Landing site: Longitude	Miles from McMurdo Station (nautical miles)	Fate	Burst altitude (km)
8/23/92	78° 12.39'	171° 40.56'	65 at 110°	Recovered	29.1
8/24/92	77° 25.75'	170° 18.74'	60 at 65°	Hit open water[b]	31.4
8/27/92	77° 34.50'	174° 52.68'	110 at 71°	No signal[b]	29.2
8/29/92	77° 11.00'	173° 23.00'	97 at 67°	Hit open water[b]	29.1
8/31/92	78° 1.76'	173° 17.30'	65–110	Recovered	29.0
9/9/92	77° 40.87'	171° 39.32'	53 at 75°	Recovered	27.9
9/9/92	77° 34.81'	172° 28.78'	79 at 80°	Recovered	32.8
9/9/92	77° 40.79'	171° 6.88'	60 at 81°	Recovered	28.1
9/14/92	77° 48.09'	172° 47.27'	77 at 87°	Recovered	27.1
9/18/92	77° 36.15'	171° 8.75'	58 at 77°	Recovered	~28
9/23/92	78° 9.81'	175° 51.25'	116 at 99°	Recovered	34.6
10/9/92	78° 50.59'	173° 48.04'	90 at 89°	Recovered	32.2

[a]*Source:* Bryan Johnson, University of Wyoming, Laramie, personal communication to Lance McCold, ORNL, June 22, 1993.
[b]Payload was not recovered.

The 0.02-mm-thick (0.8-mil-thick) polyethylene high-altitude balloons can exceed 800,000 m^3 (28 million ft^3) at altitude and weigh 1600 kg (3500 lb). At launch each balloon is charged with between 5700 and 6400 m^3 (200,000 and 225,000 ft^3) of helium gas. The payloads may exceed 1800 kg (4000 lbs). One payload flown in 1992 included about 350 kg (770 lb) of soil from Ross Island near McMurdo to measure the gamma rays emitted by soil when it is bombarded by cosmic rays while above most of the earth's atmosphere.

In response to a radio signal broadcast from an aircraft, explosive charges separate the balloon from the payload and parachute. When the payload begins to descend, it tears a panel in the balloon which then collapses and falls to earth. The payload takes about an hour to descend; the balloon is believed to reach the ground in about 15 minutes. Depending on wind strength and payload weight, balloons generally land within 48 km (30 miles) of the payload (Steven Peterson, NSBF, personal communication to G. K. Eddlemon, ORNL, September 23, 1994). Payloads have landed on the Ross Ice Shelf or on the Antarctic Plateau west of the Transantactic Mountains. Flights are terminated where there is a good chance of recovering the payload. Payloads landing on the Ross Ice Shelf are generally easiest to recover. If they cannot be terminated over the ice shelf, they are terminated where the payload is likely to land on a crevice-free area on the plateau. In the three years before the 1993–94 season, three payloads landed on the ice shelf and two landed on the plateau. The two payloads that landed on the plateau were partially recovered. During recovery the instruments are removed from the payload's aluminum framework and flown to McMurdo in a twin otter aircraft. The aluminum framework is abandoned in place because it is too large to go into the twin otter. The three payloads that landed on the ice shelf were completely recovered. No attempt has been made to recover the balloons, they have not been tracked so their landing locations are not known (Danny Ball, NSBF, personal communication to L. N. McCold, ORNL, July 1, 1993).

In December 1993 in the Ross Sea near McMurdo Station, an LDHL balloon and payload were lost due to a malfunction in the release mechanism for the payload. The payload could not be released from the balloon and both were brought down together. The payload and balloon landed in open water. An equipment manufacturing error was discovered and corrected for the LDHL Balloon Program (Sulivan and Needleman 1994).

Sullivan and Needleman (1994) also report that the current USAP policy is to target balloon and payload to land in a recoverable area close to McMurdo Station. A recovery team of five to eight persons with equipment is to move by aircraft or overland traverse to the landing sites and recover both the payload and the balloon. Balloons and payloads are to be disassembled as needed and transported to McMurdo Station for removal from Antarctica. Balloons and/or payloads that land in areas that are unsafe for recovery would be left on site to prevent exposing personnel to extraordinary risk.

Most flights carry about 230 kg (500 lb) of small steel pellets as ballast. The ballast is released as necessary to maintain flight altitude (Sullivan and Needleman 1994). During the 1992-1993 season the Long-Duration Antarctic Mass Calibration Balloon Mission carried 350 kg (770 lb) of soil from Ross Island as ballast and for research purposes. Most of this soil was dropped in eight increments of 25 to 50 kg (50 to 100 lb) as the balloon circled the continent. [Between 10 and 20 kg of the soil was recovered with the payload for analysis (Jacob Trombkta, Goddard Space Flight Center, Greenbelt, Maryland, personal communication to G. K. Eddlemon, ORNL, September 28, 1994)]. Some flights carry and release to the atmosphere up to 136 kg (300 lb) of cryogen used to maintain instruments at low temperatures (Sullivan and Needleman 1994).

2.2 BALLOONS USED IN ANTARCTICA BY OTHER NATIONS

Information on balloon use in Antarctica by other nations is difficult to obtain, but it is known that a number of stations launch rawinsondes and other balloons. For February 1992, the following stations reported launching rawinsondes: Amundsen-Scott South Pole (United States), Bellingshausen (Russia), Casey (Australia), Davis (Australia), Dumont d'Urville (France), Frei (Chile), George von Neumayer (Germany), Halley (United Kingdom), Marimbio (Argentina), Mawson (Australia), McMurdo (United States), Mirny (Russia), Molodezhnaya (Russia), Novolazarevskaya (Russia), SANAE (South Africa), Syowa (Japan), Vostok (Russia) [Jane Dionne, NSF, Washington, D.C., personal communication to Lance McCold, Oak Ridge National Laboratory (ORNL) September 15, 1993]. Their locations are shown on Fig. 1. Six of these, Casey, Davis, McMurdo, Molodezhnaya, SANAE, and Syowa, report launching balloons twice per day. In total, these 17 stations report launching 23 balloons per day. All but two of the stations, Amundsen-Scott and Vostok, are at coastal locations.

Estimating the number of balloons launched per year is complicated because the number launched by each station is uncertain. An estimate of 23 balloons per day totals 8395 balloons per year. However, the actual number could be somewhat higher or lower. McMurdo Station, for example, actually launches about 650 rawinsondes per year, somewhat less than the 730 that would be estimated from the above information. Amundsen-Scott, on the other hand launches just over 500 rawinsondes per year, substantially more than the 365 that would be surmised from the above information. In addition, some seasonal bases that are not included in the above list may launch rawinsondes to support aircraft operations or research activities. If other stations that report two balloon launches per day in February drop to one per day in the Antarctic winter, as at McMurdo, then the number of balloon launches may be a low as 7915 (11 stations at 365/year plus 6 stations at 650/year). If other stations that report only one launch per day actually launch 500/year as does the South Pole Station, the actual number of rawinsonde launches may be as large as 9880 (11 stations at 500/year plus 6 stations at 730/year). If some summer stations launch rawinsondes, the number could exceed 10,000/year.

ORNL DWG 90-1730R1

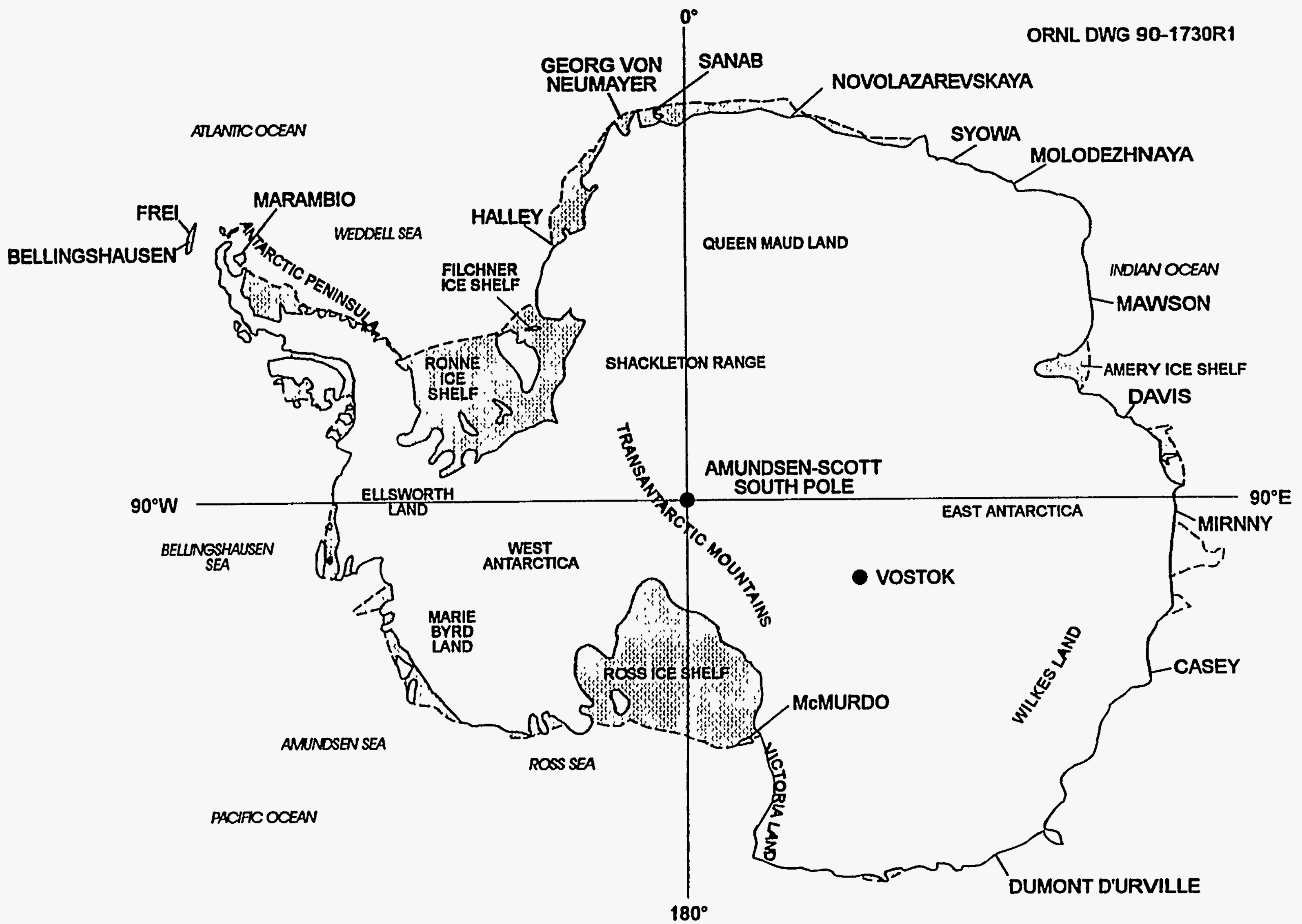

Fig. 1. Antarctic stations flying rawinsondes.

Contacts with personnel from other nations are consistent with these estimates. Australia launches approximately 2300 rawinsondes per year (Rob Ferguson, Antarctic Division, Department of the Environment, Sport and Territories, Tasmania, Australia, personal communication to G. K. Eddlemon, ORNL, June 9, 1995) (including launches from the Australian subantarctic island of Macquarle, would increase this number to over 3000). Victor N. Pomelov, Russian Antarctic Expedition, reports that one balloon per day is launched from Mivay, Novolazarevskaya, Bellingshausen and Molodezhnaya, and from the R/V Akademik Fedorov (personal communication to G. K. Eddlemon, ORNL, June 1, 1995). Based on the above information, Australia, Russia, and the United States together launch about 53,000 rawinsondes per year.

For the purpose of this analysis, we use an estimate of 10,000 rawinsonde launches per year. We also assume that the same mix of neoprene and polyethylene balloons are used at other stations as at U.S. stations. Finally, we assume that balloons launched from Vostok (if any) and Amundsen-Scott Stations are incorporated into the ice sheet and do not reach the ocean for thousands of years, so the potential number of balloons that could affect marine organisms is 9000/year.

The National Research Council (NRC 1993; 21) reports that ozonesondes are launched from Halley (U.K.) and Syowa (Japan) stations. Ozonesondes have also been launches from Juan Carlos Parimero, Livingston Island, South Shetland Islands (Spain), United Kingdom, Italian and Korean Observers, undated).

Long-duration ballooning has been practiced by the Japanese Antarctic Research Expedition (JARE) from Syowa Station (Ejiri 1993). Ejiri reports that the JARE flew two large [1500-m^3 (54,000-ft^3)] balloons in 1987 and one in 1990. One 1987 flight was unsuccessful and the other lasted about 7 days before coming down in the Wellington Sea. The second successful flight began on January 5, 1990, and ended when the balloon fell into the ocean near 90°E near the end of the month. JARE planned three additional long-duration balloon flights for 1991, intending for the balloons to return to the vicinity of the launch site at Syowa Station. Dr. Edgar Boring, University of Houston, reports that Japan launched six long-duration balloons from Syowa Station but plan to launch no more for 4-5 years; he also reports that New Zealand has launched 5 or 6 long-duration balloons (personal communication to G. K. Eddlemon, ORNL, September 24, 1994).

3. ENVIRONMENTAL CONSEQUENCES AND MITIGATION

The following resources may be affected by the use of balloons in Antarctica: opportunities for scientific research; antarctic plants and animals; aesthetic and wilderness values; rare and unique environments; historic sites and artifacts; antarctic soils, snow, and ice; and human safety. In addition, transport and support of these people and materials deployed at McMurdo and South Pole Stations to carry out the balloon programs contribute to the stations' effects on the environment.

The direct environmental effects of the balloons and their payloads occur where they return to earth. Figures 2 and 3 show the approximate landing locations of rawinsondes launched from Amundsen-Scott South Pole and McMurdo stations during the year. These locations are based on rawinsonde data and the assumptions that balloons fall at approximately twice their ascent rate, and that the wind velocities are the same as during the ascent as described in Appendix A.

Figure 2 shows that most rawinsonde balloons launched from the South Pole Station fall within about 80 km (50 miles) of the station. Most balloons that go farther than 80 km (50 miles) have travelled in the grid-west and grid-north directions. The balloons are probably incorporated into the polar ice sheet and moved slowly [about 10 m/year (30 ft/year)] toward the ocean. The speed of the polar ice sheet is variable, but if 10 m/year is typical, the balloons would take over 80,000 years to reach the Ronne Ice Shelf, and thousands of years more to reach the ocean. It is not clear what condition these balloons will be in when they reach the ocean. If they reach the high-shear zone at the base of the glacier they will likely be little more than a chemical residue. If not, they may reach the ocean in a form that is recognizable. In any case, we have treated balloons incorporated into the glacier as though they would have no further environmental impacts.

Figure 3 shows that balloons launched from McMurdo most often come down within 100 km (60 miles) of the station, but that a few may come down as much as 200 km (120 miles) east of the station. About 10% land in open water or on the sea ice, and about 10% come down on Ross Island. A few, perhaps 5%, come down on other islands or the mainland. The remainder, about 75%, come down on the Ross Ice Shelf. Most of these will eventually end up in the ocean, either blown by surface winds or carried by glacial movements.

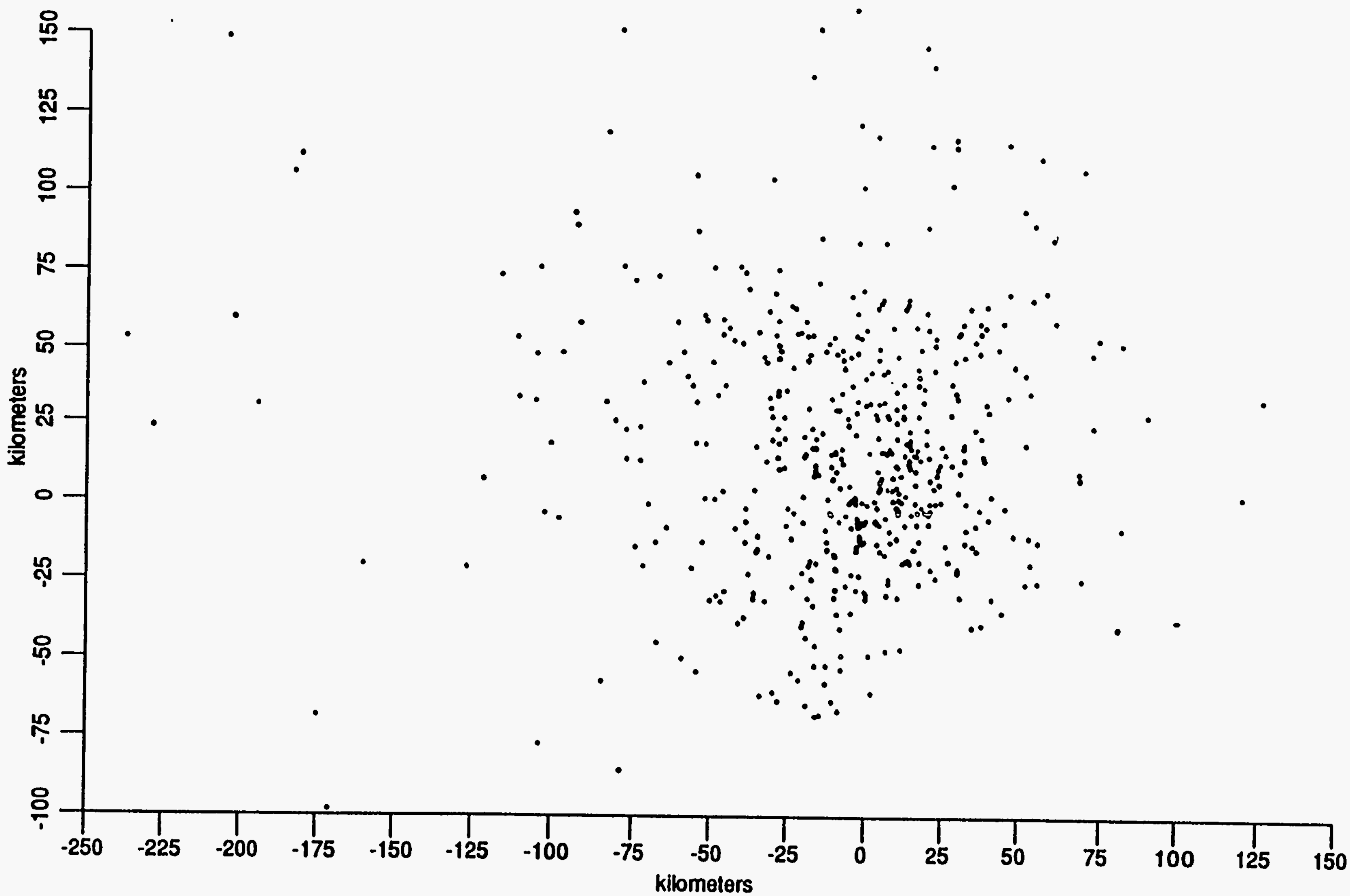

Fig. 2. Approximate landing sites of rainsondes launches from the South Pole Station from July 1, 1992, through June 30, 1993. (South Pole is indicated by postion 0,0.) *Source*: Based on data from ASA (John Giess, personal communication to Lance McCold, ORNL, September 28, 1993); see Appendix A.

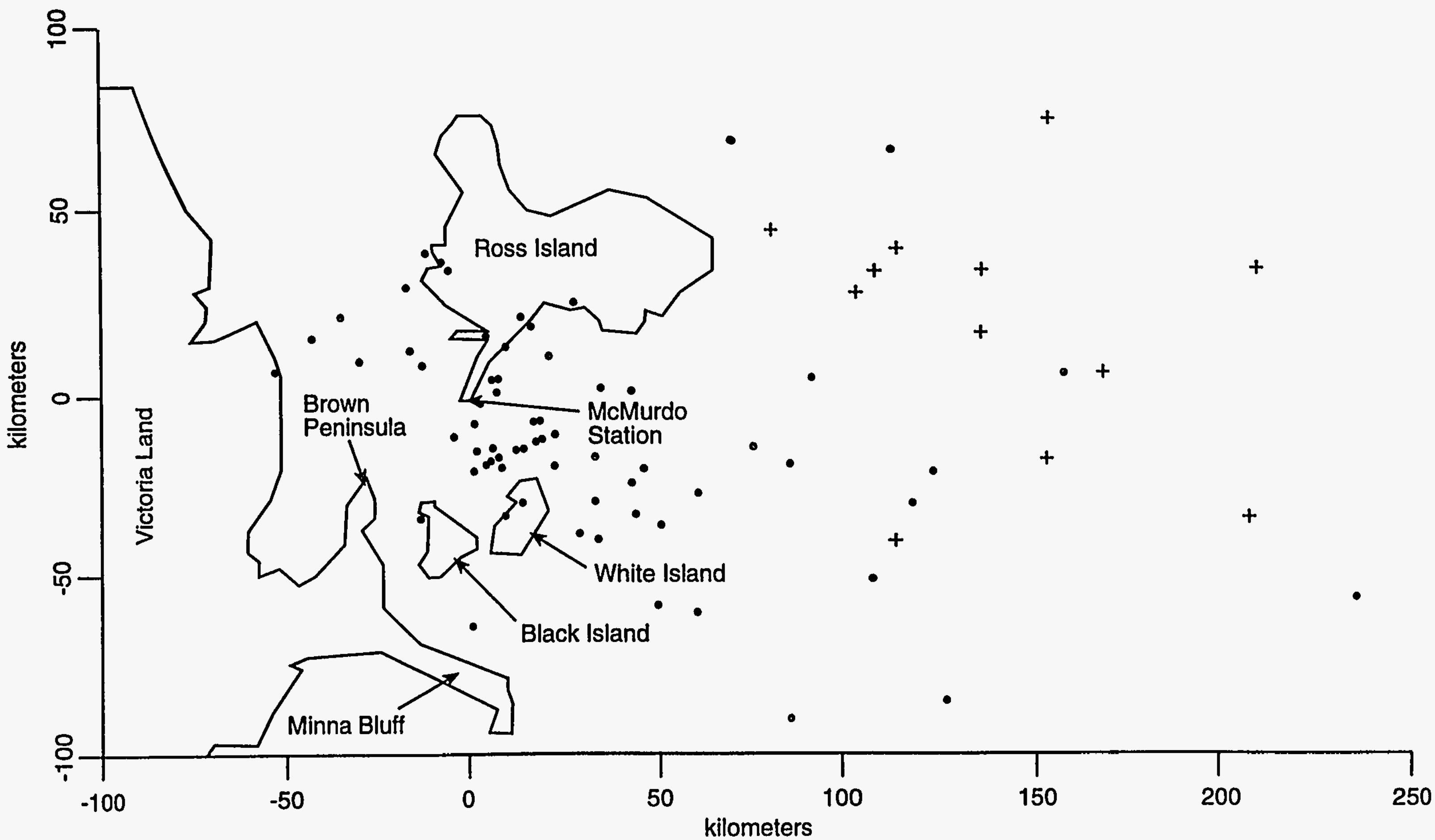

Fig. 3. Approximate landing sites of 91 rawinsondes launched from McMurdo Station between February 1 and October 29, 1991 (filled circles); and known landing sites of 12 high-value ozonesondes launched during August, September, and October 1992 (+s). (Position 0,0 is located at McMurdo Station.) *Source:* Based on data from NCDC and Table 2; see Appendix A.

3.1 OPPORTUNITIES FOR SCIENTIFIC RESEARCH

Protecting the antarctic environment for scientific research is one of the major goals of the Antarctic Treaty and the Protocol. Most USAP activities are related to the conduct or support of scientific research. In general, antarctic soils, snows, and ice are generally freer from anthropogenic contamination than those found any other place on earth. Antarctica presents an important opportunity to study the deposition and accumulation of contamination that results from global transport. The use of balloons could lead to contamination of areas that could be used for research.

Balloons and their payloads are composed primarily of inert materials. The balloons are made of polyethylene or neoprene. Both materials are subject to oxidation; however, low temperatures and humidities will retard oxidation of balloons that do not fall into the ocean. In addition, as they are covered with snow, they will be protected from the sun and wind.

Most ozonesondes are powered by lithium batteries because they maintain good performance at low temperatures. Rawinsondes are powered by alkaline or lithium batteries depending on the ambient temperature. In time the contents of these batteries may leak, but low ambient temperatures are likely to retard deterioration while the batteries remain on land or in glacier ice. Ozonesondes use electrochemical cells containing small amounts of potassium iodine and potassium bromide solutions. These solutions may leak from the cells when the sonde returns to earth, contaminating a small amount of soil or snow in the vicinity of the fallen payload. These contaminants may affect future chemical analyses of soils and ice. Most ozonesondes launched from McMurdo come down on the Ross Ice Shelf northeast of McMurdo. Because most of these remain on the ice shelf for a few decades before ending up in the sea, they seem unlikely to interfere with future research. Ozonesondes that come down on land or on the polar plateau have a somewhat greater potential for affecting future scientific research because their residence time may be thousands of years.

3.2 ANTARCTIC PLANTS AND ANIMALS

Protection of antarctic plants and animals is given a very high priority by the Antarctic Treaty. The Protocol to the Treaty requires that "activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the antarctic environment and dependent and associated ecosystems," and "activities in the Antarctic Treaty area shall be planned and conducted so as to avoid: ... (iv) detrimental changes in the distribution, abundance, or productivity of species or populations of species of fauna and flora; (v) further jeopardy to endangered or threatened species or populations of such species" (Article 3).

The Protocol prohibits taking of harmful interference with native flora and fauna except in accordance with a permit. Harmful interference includes "significantly damaging concentrations of native terrestrial plants by landing aircraft, driving vehicles, or walking on them, *or by any other means* (italics added); and any activity that results in the significant adverse modification of habitats of any species or population of native mammal, bird, plant, or invertebrate" (Annex II, Article 1). The protocol also establishes "Specially Protected Species" that are to be accorded special protection by the Parties (to the Antarctic Treaty) (Annex II, Article 3). Permits are to be given only when the taking "(a) is for a compelling scientific purposes; [and] (b) will not jeopardize the survival of the species or local population." The specially protected species (all species of the genus *Artcocephalus*, fur seals, and *Ommatophoco rossii*, Ross Seal) are listed in Appendix A to Annex II and are the same as those identified by Annex A to the Agreed Measures for Conservation of Antarctic Fauna and Flora.

In addition, the U.S. Endangered Species Act of 1973 also protects antarctic wildlife species that are listed as threatened or endangered. Section 7 of the act requires that "Each federal agency shall, ...insure that any action authorized, funded, or carried out by such agency ... is not likely to jeopardize the continued existence of any endangered or threatened species ..." Several species of antarctic whales are listed as endangered under the Endangered Species Act (Appendix B).

Balloons and their payloads could adversely affect antarctic biota through three mechanisms:

- damage to plants and animals from direct impact by falling payloads and balloons;
- ingestion of balloon and payload plastics by and subsequent injury or toxicity to wildlife, fish, and invertebrates; and
- Entanglement or other entrapment of wildlife in balloon plastic and shrouds.

The remainder of this section discusses potential impacts to antarctic biota by the three mechanisms listed above.

3.2.1 Direct Impact by Falling Payloads

The probabilities of payloads falling on birds and marine mammals is very low (Appendix C). Moreover, a falling payload generally would injure or kill at most one animal. Larger animals, such as seals and cetaceans, might not be seriously injured even by a direct hit because most payloads are small, plastic-foam-encased, packages weighing about 220 g (8 oz). Of the total of approximately 700 balloons launched each year at McMurdo Station, fewer than 50 carry payloads weighing more than 220 g (8 oz), and most of these weigh only 610 g (22 oz). In addition, balloons are launched throughout the year, but most antarctic birds are absent half, or more, of the year. For these reasons, there appears to be no reasonable chance that direct balloon payload impacts could significantly affect antarctic bird or mammal populations.

The only notable assemblages of plants known in the McMurdo area are in SSSI Nos. 11 and 12. As described in Sect. 3.4, impacts to the plants in these areas are unlikely.

3.2.2 Ingestion/Entanglement

Table 3 shows some of the more important characteristics of the balloons used in the USAP. The physical and chemical characteristics of balloon membranes, shrouds, and payload packaging can directly or indirectly affect the potential for adverse effects on biota. For example, the specific gravity of neoprene is about 1.23, compared to seawater's typical specific gravity of about 1.02 to 1.03 (Dean 1973). Neoprene balloon material, therefore, should sink in seawater (unless entrapped air, colonizing algae, or payload materials keep it afloat) where it would be less likely to interfere with mobile marine biota. The specific gravity of polyethylene, on the other hand, ranges from 0.91 to 0.96. Thus, polyethylene floats and may entrap mobile marine life or be mistaken for a jellyfish and ingested by vertebrates that favor jellyfish as food.

Nylon shrouds and parachutes and expanded polystyrene packaging around some balloon payloads may also enter the marine environment, but the quantities are much smaller than the amount of balloon material entering the environment. Nylon has a higher specific gravity (1.14–1.16) than sea water and would be expected to sink to the ocean bottom where it would be less likely to interact with mobile marine biota than the floating polystyrene.

These plastics may last many years in Antarctica. Some estimates of environmental persistence of plastics range up to 400 years (Joyner and Frew 1991). Neoprene is especially noted for its outstanding resistance to weathering, sunlight, heat, and attack by many chemicals. Synthetic plastics in general are more resistant to microbial degradation than natural polymers such as rubber (Cundell 1974). Moreover, the antarctic cold and the paucity of microorganisms able to break down these plastics may extend their lives considerably. Finally, the plastic membranes may have additional constituents such as antimicrobial and antistatic agents, antioxidants, and ultraviolet (UV) radiation inhibitors that could also extend their lifetimes. The neoprene used in the smaller balloons, for example, contains 4–5% by weight synthetic oil (plasticizer), zinc oxide, antioxidants, and other, proprietary compounds. Polyethylene balloons contain a proprietary antioxidant incorporated into the polymer and, in the larger balloons, polyester fibers are laminated onto the membrane.

The fact that plastic pollution in the marine environment can injure and kill individuals of many kinds of marine organisms including birds, seals, whales, turtles, fish, crustaceans, and corals has been amply documented (Joyner and Frew 1991; O'Hara 1988). Moreover, plastic pellets have been found in stomachs of both antarctic and subantarctic seabirds; other seabirds and seals of waters around South Georgia have received debilitating or fatal injuries from entanglement in plastic debris (Ryan 1988; Furness 1983). Ingested plastic, mostly bags and sheeting, have been found in the dead bodies of at least nine species of stranded cetaceans (O'Hara 1988). Some mammals, birds, and fish appear to be attracted to plastic objects, perhaps through curiosity, or by mistaking plastic for food or shelter. In at least one species, the northern fur seal of the Pribilof Islands, population-level effects have been attributed to plastic pollution. Scientists studying a dramatic decline in the number of these animals concluded that entanglement in plastic netting and packing straps was killing as many as 40,000 seals per year (Fowler 1987). That more population-level effects have not been demonstrated may be due more to inadequate knowledge than to an actual absence of population effects.

The existing literature on plastic pollution and effects in the marine environment does not indicate that any substantial adverse effects of plastics on marine biota (e.g., at the population level) are occurring in antarctic waters. Documented instances of ingestion of plastics by antarctic birds have generally involved pellets intended for use as feedstocks in plastics manufacturing. Individual organisms may occasionally come across balloon material and be injured or killed by accidental or deliberate ingestion of the material. Entanglement with balloon material is probably less likely than entanglement in plastic netting, filament, and high density plastics such as plastic six-pack rings used in packaging. The most likely candidates for ingestion of balloon material are probably the various seal and whale species residing in or visiting antarctic waters. Because all of the great whale species are considered endangered by the National Marine Fisheries Service

Table 3. Biologically relevant features of balloons used at McMurdo Station[a]

Material	Use[b]	Weight (kg)	Volume (m^3)	Surface area (m^2)	Length[c] (m)	Launches[a]/year	Total effective area per year[d] (m^2)	Total length per year (m)
Polyethylene	O	2.6	210	170	12	~100	8,500	1,200
Polyethylene	O	2.8	540	320	16	25–30	4,800	480
Polyethylene	O	4.8	1,530	640	23	9–12	3,800	280
Polyethylene	O	8.2	4,000	1,200	31	3	1,800	100
Polyethylene	L	17	7,000	1,800	37	2-5	4,500	190
Polyethylene	L	1,600	790,000	41,400	180	2	42,000	360
Subtotal polyethylene						≤152	66,000	2,600
Neoprene	R	0.65	2.2	8.2	2.5	~550	2,300	1,400
Total all balloons						~700	68,000	4,000

[a]Balloons launched from the South Pole Station are not considered in this analysis because it would be over 80,000 years before they could reach the ocean.
[b]O = ozonesandes, L = long-duration, high-altitude balloon flights; R - rawinsondes.
[c]Back-calculated from volume; length taken as πr where r = radius.
[d]Effective deflated area is taken to be half the surface area.

(NMFS) and the International Whaling Commission, much of the following discussion focuses on potential impacts on these animals.

Benthos. If a total of about 550 neoprene balloons per year eventually enter and sink in the approximately 100,000 km^2 (39,000 $miles^2$) region of the Ross Sea bounded by the ice shelf and a line paralleling but 100 km (60 miles) out from the ice shelf, then a maximum of about 2300 m^2 (25,000 ft^2) of the sea bottom and its associated benthic community could be covered by neoprene membranes each year. [Because these membranes would be expected to incur some degree of folding and wrinkling, the actual area covered annually could likely be significantly less than the maximum of 2300 m^2 (25,000 ft^2)]. Although mobile organisms such as starfish and pycnogonids could escape from under the neoprene, sessile plants and animals (e.g., attached algae, sponges, and anemones) might be harmed or killed through interference with gas exchange, nutrient uptake, food capture, and excretion of waste products. However, the maximum 2300-m^2 (25,000-ft^2) area represents only $2.3 \times 10^{-6}\%$ of the total benthic area in the region. Even if balloon launches were to continue for 1000 years at double the current rate and neoprene should last 1000 years in this environment (that is, 1.1×10^6 balloons on the sea bottom at any one time), no more than 0.005% of the benthic community would be affected. Moreover, the neoprene membranes themselves would likely be colonized by benthic organisms within a fairly short time (from months to years). Anthony Amos, University of Texas Marine Science Institute, reports that he has observed many instances of colonization of plastics in marine environments, sometimes with cycles of colonization and decolonization as the plastic alternately rises and sinks (personal communication to G. K. Eddlemon, ORNL, September 9, 1994).

Marine mammals. Adverse effects on individual seals and seabirds may occur in Antarctica as a result of the current use of balloons. However, the apparent health and size of seal and seabird populations in Antarctica suggest that population-level effects are unlikely in the foreseeable future. In contrast, all great whale species are endangered, and the limited information available on whale biology and behavior suggests that they may be especially vulnerable to plastic pollution of the seas. The following analysis of the potential impacts of balloon operations on great whales focuses on the blue whale which is one of the three endangered whales that inhabit the southern ocean with the smallest populations (Appendix B).

The maximum possible burden of balloon plastic in the 100 × 1000-km (60 × 600-mile) strip of the Ross Sea adjacent to the ice shelf (after transport of downed balloons to the sea reaches equilibrium at an unknown time in the future) may be estimated from the information presented in Table 2. These estimates (Table 3) yield an annual input to the Ross Sea of 3900 kg (8600 lb) or an effective area of 64,000 m^2 (600,000 ft^2) (0.5 of total balloon surface area) of plastic and rubber from balloons launched from McMurdo Station. This region has an area of approximately 100,000 km^2 (39,000 $mile^2$), so 64,000 m^2 is a negligible fraction of the region under consideration. However, the cumulative length of floating plastic may be a more meaningful index of biological interaction than mass or surface area because whales and some seals swim considerable distances through the area, and the probability of whales or seals encountering floating plastic sheeting should be proportional to the total cumulative length of the material. As shown in Table 3, current balloon operations at McMurdo could eventually result in 3.8 km/year (2.4 miles/year) of neoprene and polyethylene entering the marine environment (at the unknown future time when balloons that previously landed on the Ross Ice Shelf are entering the ocean at the same rate as new balloons are being deposited on the ice shelf). For assumed mean persistence of balloons in the ocean of 10 years and 50 years, the cumulative length of plastic floating in the southern ocean due to McMurdo balloon launches would be as much as 38 km (24 miles) after 10 years and 190 km (120 miles) after 50 years. Shredding and partial breakdown of the larger polyethylene balloons may actually result in greater total length (and potential hazard).

Although contact with balloons by active swimmers such as whales in these scenarios would be likely, and injuries and deaths of large marine organisms in other seas have been attributed to plastic bags, the probability that an encounter with balloons would result in injury or death is unknown. Nevertheless, if up to 7.6 km (4.7 miles) of floating polyethylene were to accumulate (based on a two-year residence time) in a 100 × 1000-km (60 × 600-mile) zone visited by blue or humpback whales for feeding, there might be many encounters between whales and the balloon material. Given certain assumptions about the behavior of balloons and whales, it is estimated that each whale spending the season in the Ross Sea will encounter an average of 1.9 balloons (Appendix D). The effect of this encounter rate on blue whale populations depends on the proportion of encounters that lead to death and the fraction of the population that spends the season in the Ross Sea area. The fraction of encounters leading to death of the animal is completely unknown. The information currently available indicates that marine mammals are sometimes killed by ingestion or entanglement with plastics in the marine environment. For this analysis, we have assumed that one encounter in one hundred leads to the death of the animal.

The number of blue whales that spend the season in the Ross Sea is unknown. The perimeter of Antarctica is about 16,000 km (9900 miles) long, and the Ross Sea extends about 1000 km (600 miles) along the ice shelf. If the blue whale population were evenly distributed within a 100-km (60-mile) zone around the coast of Antarctica, then about 6% of the population would be found in the 100-km (60-mile) zone along the ice shelf in the Ross Sea. Thus, if the southern population of blue whales is 1000 animals, under the above assumptions about 60 would be found in the Ross Sea during the austral summer. Assuming that 1% of encounters lead to death, there would be about 110 encounters and 1 fatality per year.

The actual population in the Ross Sea could be higher or lower, depending to a large extent on the abundance of kill in the area. If, for example, only 1% of the population spends the summer in the Ross Sea, about 19 encounters per year and one fatality about every 5 years could be expected. Although the fatality-to-encounter ratio could actually be much lower, given the state of our knowledge and the low numbers and reproductive rates of these animals, concluding that the potential effects are negligible does not appear to be justified.

3.2.3 Cumulative Impacts

Of greater concern than the effects of balloons launched from McMurdo Station are the cumulative effects, especially on endangered whole species, of all balloon operations around the antarctic continent. We estimate that about 9000 weather balloons (including about 750 from McMurdo) are launched from coastal stations around the continent each year (Sect. 2.2). To estimate potential cumulative effects, we also made the following assumptions:

- that the rate of balloons entering the ocean either directly or through transport by katabatic winds and ice flows equals the coastal station launch rate of 9000 per year,
- that the balloons are randomly distributed throughout the approximately 3.0×10^7 km^2 area south of the Antarctic Convergence and north of the antarctic coasts and permanent shelf ice, and
- that blue whales swim continually at the surface south of the Antarctic Convergence for 150 days each year.

Because lifetime of balloons in the ocean is unknown, we estimated the number of encounters for the following scenarios.

- Scenario 1: no more than 1 year's worth of launched balloons is adrift at any one time (i.e., the balloon disappearance rate equals the balloon launch rate, 9000 balloons/year);

- Scenario 2: all balloons from 10 years of launch operations are adrift at any one time (90,000 balloons); and
- Scenario 3: balloons remain afloat in the southern ocean for 50 years (450,000 balloons).

(Most stations have been launching balloons for less than 20 years so the third scenario represents a hypothetical situation a few decades in the future.)

Using the method described in Appendix D, Scenario 1 gives a probability of about 0.06 that any individual whale will encounter a balloon each year. If the number of balloons floating in the southern ocean is 90,000 (Scenario 2) the probability of an encounter is about 0.6; that is, about 60% of the whales would encounter a balloon each year. If, as we assumed above, 1 fatality occurs for each 100 encounters, then balloon encounters would cause the deaths of 0.6% of the whales in the southern ocean each year. Scenario 3 represents a hypothetical future situation if balloons prove to be long lived in the ocean. If Scenario 3's assumption that balloons are long lived is correct, the balloon-induced fatality rate could increase substantially from current levels to nearly 3% per year as balloons accumulate in the ocean. Although it seems likely that some mechanism would clear the oceans of most balloons in less than 50 years, other man-made pollutants, including plastics, have accumulated in the biosphere with no indication of rapid removal.

There are many uncertainties involved in these estimates besides the persistence of balloons in the ocean. One of the most important uncertainties is the actual distribution of whales and balloons. The method of Appendix D is based on an assumed random distribution of both. If winds or currents concentrate balloons in the same areas as whales' natural prey, the encounter rate could be much higher than estimated here. For instance, if the concentration of balloons is twice the average concentration in areas where prey are found in high concentrations and the whales spend 5 times as much time in such areas than in other parts of the ocean, the number of encounters could be 10 times the estimate provided above; that is, about 5 encounters per whale per year. Fatalities (Scenario 2) could be 5% of the population per year. On the other hand, if whales concentrate their activities in a relatively small part of the southern ocean and balloons tend to accumulate in other areas, then the number of encounters and fatalities would be proportionately smaller.

Little is known of natural mortality in most whale species, but some researchers have suggested 4% per year as a reasonable figure for adult blue, fin, and right whales, and 7.5% for sei whales (Braham and Rice 1984; Mizroch et al., 1984a,b,c). Immature whales probably have somewhat higher natural mortality rates. Thus, under Scenario 2, the loss rates due to balloons might approach 10% of the natural mortality rate. The absence of evidence for recovery of most baleen whale stocks, and the existence of other anthropogenic factors such as other sources of pollution, whale-ship collisions, harvesting of prey (e.g., kill and small schooling fish) increase the concern for these species' prospects. For endangered species such as the blue, humpback, and right whales, losing even a few animals per year to balloon operations might be a stress these dangerously small populations (1,000 to 10,000 individuals each) cannot sustain.

Smaller baleen whales such as the minke whale and the toothed whales (Odontoceti) could also be harmed by floating balloon material. Most reports of whales ingesting plastic bags are for toothed whales. It is likely that many encounters with drifting material will occur and some of these encounters may result in ingestion or envelopment and death. Of the smaller baleen whales and many toothed whales that may occur in the southern ocean, however, only the sperm whale has been accorded endangered status under the Endangered Species Act, and even this endangered animal enjoys relatively high population estimates (on the order of 400,000 or more in the southern hemisphere) compared to the endangered baleen whales. Moreover, the sperm whale's habit of feeding on squid and other relatively large prey at considerable depths should greatly reduce the probability of interactions with balloons drifting at or just beneath the surface.

3.3 AESTHETIC AND WILDERNESS VALUES

The antarctic environment has been internationally recognized for its aesthetic and wilderness values (Protocol, Article 3). These values are widespread features of the antarctic landscape, but are readily diminished by evidence of human activities.

Except for the large, long-duration balloons, the balloons and payloads used by the USAP in Antarctica would not be readily visible except from close range. Consequently, their impacts on the aesthetic values of Antarctica are primarily a concern for persons who come upon them while engaging in other activities.

Rawinsondes and ozonesondes return to earth after their balloons burst. A person coming upon one of these devices will find an expanded-polystyrene box attached to a clear or amber plastic bag lying on the ground or snow. Generally, the payload and balloon could be picked up and carried away, and the aesthetic quality of the site restored, but there would be an adverse impact to the aesthetic experience of the persons who find a balloon.

Wilderness values relate to a sense of solitude and isolation. A used rawinsonde or ozonesonde found in Antarctica is unambiguous evidence of civilization's proximity. Travelers who come upon a sonde may take it with them to save future travelers the disruption of finding it again, but the experience will affect their sense of remoteness from civilization. Nearly 600 weather and ozonesonde balloons per year are launched at the South Pole Station. As shown by Fig. 2, most balloons land within 100 km (60 miles) of the station. So few of the balloons launched from the South Pole Station land beyond 250 km (150 miles) that they are unlikely to be encountered and thus to have any appreciable effect on aesthetics and wilderness values.

Snow accumulates at the South Pole at a rate of about 15 cm/year (6 in./year). Rawinsondes are small enough to be covered by a year's accumulation of snow. Ozonesondes are larger and may require 2–3 years to be covered. Thus, 500 to 600 sondes should be visible at the surface at any time. If we assume conservatively that all balloons are distributed evenly with 50 km (30 miles) of the station, their density would be about 0.064/km^2 (0.17/mile^2). Members of an expedition travelling to and from the pole would traverse 100 km (60 miles) of the area with balloons. If they are assumed to be able to see 30 m (100 ft) on either side of their path, they would have seen an area of almost 6 km^2 (2.4 mile^2) and they would have about a 40% chance of seeing one balloon and payload. Weather and lighting conditions, and the stress of travel may reduce the likelihood of observing a sonde that had returned to earth. At least one balloon has been found and brought in to the station by a party skiing to the Pole (John Gress, Antarctic Support Associates, Denver, Colorado, personal communication to Lance McCold, ORNL, Oak Ridge, Tennessee, September 29, 1993).

The situation near McMurdo Station is more complicated. The McMurdo area has zones of substantial snow accumulation, zones of ablation, seasonally open water, and areas of bare soil. The aesthetic impact of a balloon would depend on its location. Balloons in snow accumulation areas would have little impact because they would soon be buried. Balloons on snow-free areas like Black Island, the Dry Valleys, or snow-free parts of Ross Island have more potential for significant aesthetic effects than balloons that land in snow-covered areas because the balloons may remain exposed for many years and because they will be more visible against a dark background than a white one.

The probability of a balloon landing on Black Island appears to be between 10 and 50 per 1000 km^2/year (between 3 and 13 per 100 mile^2) (Appendix A). Black Island is about 150 km^2 (58 miles^2) in area, so between 1 and 8 balloons per year would be expected to come down on the island. Because they will not be covered by snow, they may remain in evidence for many years;

however, Black Island is so windy that most balloons that land there may be blown off the island. The situation on Brown Peninsula [about 15 km (9 miles) west of Black Island] is very similar to Black Island. It is about the same size as Black Island and may have about the same probability of a balloon coming down on it. However, as shown by Fig. 3, because Brown Peninsula is farther off the main track of balloon landing sites, the probability of landings these may be still lower than at Black Island. Brown Peninsula is also a very windy place so some balloons that land there may be blown onto the ice shelf.

The dozen large [1500 and 4000 m^3 (54,000 and 141,000 ft^3)] balloons launched from McMurdo that carry ozonesondes and particle detectors tend to land somewhat to the east of the rawinsondes. [The payloads parachute down and are often recovered (see Sect. 2.1.2.)] These balloons are larger than the others and their visual impact may be somewhat greater.

The balloons from the long-duration flights are of a completely different scale, and in the unlikely event that someone came upon one, they would be drawn by curiosity to examine it. Upon landing, these balloons form a pile of plastic about 8 m (25 ft) in diameter and up to 1 m (3 ft) in height (Danny Ball, National Scientific Balloon Facility, Palestine, Texas, personal communication to Lance McCold, ORNL, July 1, 1993). Though transparent in flight, these balloons have a whitish translucent appearance when at rest on the earth. None of the seven very large balloons of this type that have been used by the USAP to date have been recovered. The aesthetic impact of the balloon depends on its location. One of these balloons that comes to rest in a snow accumulation area will be buried within a few years, and will no longer have any effect on aesthetic or wilderness values. A balloon that comes to rest in one of the snow-free areas or in an ablation area would remain visible for many years. As the wind breaks a balloon into smaller pieces, those pieces will be scattered around increasing the effects on aesthetic and wilderness values. These large, long-duration balloons are cut down by radio signal from an airplane sent up to terminate the flights; terminating the flight at a place from which the balloon could be recovered, or in locations where accumulating snow would soon cover the balloon could reduce the wilderness and aesthetic impacts.

3.4 SPECIALLY VALUED AREAS

Certain antarctic locations have unique environmental features or are especially valued because of activities that are or may be conducted there. The Antarctic Treaty designates certain areas as Sites of Special Scientific Interest (SSSI) or Specially Protected Areas (SPA) that are to be managed so as to protect the resources for which they were designated. This section presents estimates of the likelihood of balloons landing in sensitive areas in the McMurdo vicinity. The methods used to estimate these likelihoods and the limited rawinsonde data available for McMurdo are described in Appendix A. Because the data for McMurdo is poor, there is a considerable uncertainty associated with these estimates. (There are no SSSIs or SPAs in the vicinity of the South Pole Station so none could be affected by balloon flights initiated there.)

Arrival Heights SSSI (No. 2) (at the north edge of McMurdo), was established for the radio quiet conditions that are important to scientific research being conducted there. Balloons returning to earth in Arrival Heights SSSI would not adversely affect radio quiet conditions because they emit no radio-frequency electromagnetic radiation after their batteries are exhausted.

SSSI No. 4, Cape Crozier, Ross Island, comprises 40 km^2 (15 $mile^2$) and includes areas where Adelie penguins nest and the adjacent fast ice where the emperor penguins breed. The SSSI is located approximately 90 km (54 miles) east-northeast of McMurdo. The site was designated because the Emperor and Adelie penguin colonies are subjects of long-term studies of population dynamics and social behavior in order to restrict access to scientists engaged in investigations at the site. A balloon falling to earth in one of the colonies would cause disruption that might interfere with breeding success of some individuals. The probability of a balloon or payload falling within the 40-km^2 (15-$miles^2$) area is between about 0.2/year and 0.3/year. That is, a balloon would be expected to fall into SSSI No. 4 every 3–6 years. Because only a fraction of the area is occupied by penguins, the likelihood of affecting penguins is still lower.

White Island SSSI (No. 18) [about 35 km (22 miles) south-southeast of McMurdo] was established to protect a small and isolated breeding population of Weddell seals that live along the northwest side of the island. Seals living in White Island SSSI may be attracted to and entangled in balloons that fall to earth there. White Island SSSI encompasses an area about 5 × 30 km (3 × 19 miles). The likelihood of a balloon coming down in this SSSI is between 1/year and 22/year. Consideration should be given to searching the White Island SSSI for any balloons that come down there to minimize the likelihood of adverse effects to the seal colony. Ward Testa, University of Washington, who is a long-term student of Weddell seals, reports that he has not observed interactions between Weddell seals but would not expect them to exhibit any interest in balloons in their vicinity (personal communication to G. K. Eddlemon, ORNL, September 3, 1994).

SSSI No. 1, Cape Royds, about 37 km (23 miles) north-northwest of McMurdo Station, was established in the Cape Royds ecosystem because of ongoing research on Adelie penguins. Cape Royds SSSI is a small area, about 0.003 km^2 (30,000 ft^2). The management plan restricts "Depositing of any pieces of equipment or materials that would in any way hinder re-occupation of nests by penguins." The likelihood of spent balloons landing in the SSSI is low, probably between 9 and 400 per 10^6 years.

SSSI No. 10 and SPA No. 20 "New College Valley," Caughley Beach, Cape Bird, Ross Island, is located about 70 km (43 miles) north of McMurdo Station. The areas were designated because they are the most extensive area of moss, algae and, lichens in southern Victoria Land. The terrestrial ecosystem is the subject of long-term research. The SPA is intended to serve as a conservation reserve for the SSSI because of the susceptibility of the cryptogamic vegetation to damage from trampling. A balloon or payload falling to earth in the SPA or SSSI could cause damage to the organisms and ecology of the area. The total area of the SPA and SSSI is about 0.3 km^2 (0.13 $mile^2$) and the probability of a balloon or payload landing in the Cape Bird SSSI or SPA is low, between 0.9 and 10 per 1000 years.

SSSI No. 11, Tramway Ridge, Mt. Erebus, Ross Island, is a 0.01-km^2 (0.004-$mile^2$) area of high-altitude warm-ground associated with the fumarolic activity of Mt. Erebus. The area is of interest to botanists, phycologists and microbiologists. The area is sensitive to trampling and introduction of alien biota. The management plan for the area says, "Sterile protective overclothing should be worn and footwear should be sterilized before entering the site to minimize the risk of introducing alien biota to the geothermal areas." A balloon or payload falling into the area could damage vegetation or introduce alien biota to the area. The site is located about 37 km (23 miles) north of McMurdo Station. Based on the trajectories of balloons launched from McMurdo, the probability that a balloon or payload would fall within this SSSI is low—between about 0.3 and 1 per 1000 years.

Ice-free areas are rare in Antarctica but there are several in the McMurdo vicinity. Most notable are the Dry Valleys, between 80 and 160 km (50 and 100 miles) west of McMurdo. In addition, there are ice-free areas on Ross Island, Black Island, and a small number of other places near McMurdo. The Dry Valleys are areas of active scientific research where terrestrial biological and geological forces are unusually active. Balloons falling to earth in the Dry Valleys or other ice-free areas have some potential for disrupting natural processes there by covering an area of ice-free earth or part of a frozen lake, or by contaminating the area with exogenous chemical compounds. If they landed in the Dry Valleys, the very large balloons used for long-duration flights would be most likely to have significant effects because of the large area they cover [about 50 m^2 (500 ft^2)]. However, they are let down by remote control and sensitive areas are avoided, so such a balloon is not likely to land in the Dry Valleys. Rawinsondes and ozonesondes are unlikely to land in the Dry Valleys because the wind seldom blows strongly enough in their direction to let them travel that far. The available data on historic balloon launches suggests that the probability of a balloon landing in the Dry Valleys is less than 3/1000 km^2-year (1/100 $mile^2$-year). The Dry Valleys encompass an area of some 500 km^2 (200 $miles^2$), so fewer than 2 balloons per year would be expected to land in the area. However, because the estimate of 3/1000 km^2-year is based on one rawinsonde (out of 91) that travelled less than 75 km (47 miles), the probability of balloons landing in the Dry Valleys is probably much less than 2/year.

There is one SSSI designated in the Dry Valleys. SSSI No. 12 is a 1 km^2 (0.4 $mile^2$) area located between Canada Glacier and Lake Fryxell in Taylor Valley, Victoria Land, about 90 km (54 miles) west-northwest of McMurdo. The area was established because the site contains some of the richest plant growth (algae and mosses) in the southern Victoria Land Dry Valleys. The scientific value of these plants necessitates prevention of trampling and water quality degradation and to regulation of sampling. A balloon falling on the area of significant vegetation growth could have an effect similar to trampling. The immediate physical damage would be less than trampling, but covering the plants with plastic could cause greater long-term effects. The probability of a balloon falling in this SSSI (which is much larger than the actual area of plant growth) is less than 3/1000 years.

3.5 HISTORIC SITES AND ARTIFACTS

Certain sites have been important in the brief history of man's presence in Antarctica. Some of those sites and the artifacts that remain are considered historic resources. Through the 16th Antarctic Treaty consultation meeting, 59 historic monuments have been identified. In addition, two other monuments in McMurdo, Our Lady of the Snows Shrine and the Raymond Smith Monument, are accorded historic status by the USAP (Division of Polar Programs 1992). This section describes the potential for impact to historic sites near McMurdo and the South Pole Stations.

Balloons are unlikely to adversely affect historic sites or artifacts. Historic sites are scarce, and except for the large balloons used for long-duration flights, balloons and payloads are not heavy enough to cause damage to historic sites. The only historic site near the South Pole Station is the flag mast erected in December 1965 at the South Geographical Pole by the First Argentine Overland Polar Expedition. Because it is buried beneath the snow, neither a balloon nor its payload could harm it.

Historic structures near McMurdo include Scott's Hut at Hut Point, built in February 1902 by Robert Falcon Scott; a cross at Hut Point erected in 1904 by the British Antarctic Expedition (1901–04) in memory of T. Vince, a member of the party who had died nearby; a cross on Observation Hill, erected by the British Antarctic Expedition (1910–13) in memory of Captain Robert Falcon Scott's party, which perished on the return journey from the South Pole, March 1912; and the Richard E. Byrd historic monument erected at McMurdo Station in 1965. These structures could be damaged if either the balloon or payload from a long-duration balloon flight were to fall upon them. However, no effect is expected because, due to the risk to humans, these flights are terminated away from McMurdo and these historic structures.

Other historic structures on Ross Island include a hut at Cape Royds, built in February 1908 by Earnest Shackleton; a hut at Cape Evans built in January 1911 by Captain Robert Falcon Scott; a cross on Wind Vane Hill, Cape Evans, erected by the Ross Sea Party of Earnest Shacklestonʼs Trans-Antarctic Expedition (1914–16); and a stone hut at Cape Crozier, constructed in July 1911 by Edward Wilson's party (British Antarctic Expedition, 1910–13) during the winter journey to collect emperor penguin eggs. These structures also could be damaged by either the balloon or payload from a long-duration balloon flight. Again, no effect is likely because long-duration balloon flights are terminated away from Ross Island and these historic structures.

3.6 ANTARCTIC SOILS, SNOW, AND ICE

Annex III of the Protocol requires that most solid and hazardous wastes be disposed of by removing them from Antarctica. Among the items that must be removed, the Annex specifically mentions electrical batteries, polystyrene foam, rubber, and "all other plastic wastes." These prohibitions evidently were agreed on to prevent harm to antarctic wildlife and to prevent contamination of pristine antarctic soils, snow, and ice. Section 2 reports that balloons are made of rubber or plastic, the payloads are usually enclosed in polystyrene foam boxes, and alkaline and lithium batteries power all but a few special payloads.

Antarctic soils, snow, and ice generally have less anthropogenic contamination than is found any other place on earth. This characteristic makes the antarctic environment a valuable resource for certain kinds of research. One risk of human activity in Antarctica would be the inadvertent contamination of these substrates. Because balloons and their payloads come down in unpredictable locations, there may be the potential for contamination of antarctic soils, snows, and ice.

Three possible sources of chemical contamination have been identified: lithium and alkaline batteries used to power all sondes, the potassium chloride/bromide solution used in ozonesondes, and the antioxidants and UV inhibitors used in all balloons (Sections 2.1.1, 2.1.2, and 3.2.2). Batteries are sealed chemical reaction cells designed to contain their contents; however, in time most batteries will leak. Antioxidants and UV inhibitors are bound in the neoprene and polyethylene balloon materials; they leach out only slowly in temperate conditions. The fate of these compounds in the antarctic environment is not known. The cold and dryness of the antarctic continent slow the rate of most chemical reactions. In addition, most things that fall on the ice-covered parts of the continent eventually end up in the ocean. These facts suggest that contamination of antarctic soils, snows, and ice would be localized phenomena.

Rawinsondes have been flown from U.S. stations in Antarctica since the Geophysical Year in 1957. In addition to over 500/year at both McMurdo and South Pole Stations, rawinsondes have been flown at Byrd Surface Camp, Ellsworth, Wilkes, Hallett, and Little Rockford (79°30'S, 147°19'W). The United States is not the only nation flying weather balloons in Antarctica. All stations that conduct aircraft operations use at least some weather balloons. In 1992 rawinsondes were flown daily from 17 antarctic stations (Fig. 1). For each station where balloons have been or are being flown, such as around McMurdo and the South Pole Station, there will be a region with many small affected areas. Other sources of soil, snow, and ice contamination are atmospheric emissions from aircraft, vehicles, and power plants, and other debris incidental to human activities. Together, these sources of contamination may have the potential for making areas around Antarctic stations unsuitable for some kinds of scientific research.

The 270 kg (500 lb) of ballast dropped by long-duration balloon flights is another source of contamination. Usually this ballast consists of small steel pellets that are dropped in about eight 250 to 50-kg (55- to 110-lb) increments. Dropped from altitudes above 30 km (100,000 ft), the pellets are likely spread over a wide area by the time they reach the surface. Future scientists studying antarctic snow, ice, or soil may be confused by the presence of small steel pellets in these samples if they are unaware of their true origin and attempt to ascribe a natural origin to them. The soil used as ballast may be even more confusing because it will be harder to discern its anthropogenic origin.

The USAP has reviewed balloon launches and concluded that they are consistent with its waste permit. These considerations are documented by a memorandum to the USAP Master Permit File (reproduced 1995, Appendix D).

3.7 HUMAN SAFETY

Human safety is a continual concern in Antarctica. Many of the rawinsondes and balloons are used for the purpose of ensuring the safety of Antarctic aircraft operations and the people involved in them. Not using weather balloons to support aircraft operations would entail somewhat greater risk to human life than doing so.

Balloon launches themselves usually do not carry a significant risk to human health. The people involved in the launch prepare the payload, move it outside, inflate the balloon, attach the payload when the balloon is adequately inflated, and release the balloon. Launching the large, long-duration balloons is much more involved because of the sizes of materials involved. The mass of the payload and balloon are so large that anyone struck by them could be seriously injured, but pre-launch and launch precautions make such an incident very unlikely (Steven Peterzen, NSBF, personal communication to G. K. Eddlemon, ORNL, September 23, 1994). These activities are not considered extraordinarily risky.

Falling balloons and payloads could be hazardous to someone at the site of impact. The large balloons used in long-duration flights fall at a rapid rate and could easily crush any person they might land upon. The payloads which weigh over 1000 kg (2200 lb) fall more slowly, but they could also crush a person upon which they landed. The risk to people is negligible, however, because these balloon flights are terminated by radio control above unoccupied areas.

Rawinsondes and ozonesondes, including their balloons, are relatively light [1–3.4 kg (2–8 lb)], but some of the ozonesondes with additional detectors are heavier [payloads of 3–4 kg (6–9 lbs) and balloons of 5–8 kg (10–20 lbs)]. These are light enough that injuries would be more likely than fatalities if one were to hit a person. As shown by Fig. 2, there is a small chance that a balloon and payload will land at the South Pole Station. Because the number of people out and about is usually small, the likelihood of an injury is small. Figure 3 shows that rawinsonde balloons launched at McMurdo may occasionally come down in McMurdo but most balloons come down well away from populated areas. The risk of injury to people is small.

3.8 LOGISTICAL IMPACTS

Balloons flown from the South Pole Station require two to three flat racks of compressed helium each year. Each flat rack weighs 9100 kg (20,000 lbs), which is a full load for an LC-130 flight from McMurdo to the South Pole Station. Because the weight difference between a full and empty rack is small, each empty flat rack also makes a full retrograde load from the South Pole Station to McMurdo. In addition, a year's supply of balloons and sondes weighs 1400 to 2300 kg (3000 to 5000 lbs), and comprise 15–25% of a LC-130 load. Launching, tracking, and recording data from rawinsonde and ozonesonde balloons requires 3–10 person-h/day.

All of the above requirements contributing to the operational demands on the South Pole Station. The station's berthing, dining, water, and electrical systems operate near capacity during much of the summer season; the person who performs these functions contributes to the demands on the station. All people and supplies go in and out of the station on LC-130s; thus LC-130 space a critical link that constrains all other activities at the South Pole Station. Aircraft operations are also the dominant source of hydrocarbon and carbon monoxide air pollution at the station (75% and 65%, respectively) (NSF 1991, 5-33).

Balloon launches at the South Pole Station also contribute to the logistical requirements on McMurdo Station. About 300 LC-130 flights/year depart from and return to McMurdo for inland sites. Nearly 180 of these flights support activities at the South Pole Station. Each flight requires a flight crew of five plus a ground crew to repair and maintain the aircraft. All these people require additional support from other people. The cumulative effect is to increase the amount of activity and the environmental footprint of McMurdo.

Approximately three flat racks of helium are used for the rawinsonde and ozonesonde flights from McMurdo Station each year. In addition, eight racks of helium cylinders are used to launch two high-altitude, long duration balloon flights per year. All helium used for balloon flights (including those at the South Pole Station) require 13 or 14 helium cylinder racks each year. These cylinder racks are brought in each year on the cargo ship and the empty cylinders are retrograded on the ship.

The high-altitude, long-duration balloon flights during the 1992–93 season involved 42 people (with projects S-116, S-145, and S-146) on station for typical stays of 4–5 weeks during the period from mid-November through the end of January [Antarctic Support Associates (ASA) 1992]. Together, they were budgeted 70 LC-130 hours, 5 helicopter hours and an unspecified number of twin otter hours for tracking data recovery and payload recovery.

Ozonesondes are flown from McMurdo by project S-131. The field team consists of five people with an average stay of about eight weeks between late August and late October. The project uses approximately 36 helicopter hours to recover the 12 high-value payloads they fly.

Comparison of the number of scientists (ASA 1992) with the total McMurdo population reveals that the typical ratio of scientific and technical project personnel to construction and support people in McMurdo is about 1:7 during mid-January. Many of the support people are not there to support individual science projects, so the ratio of project people to support people may be much lower, say 1:3. If these projects were not being performed (and no other projects took their place) the population of McMurdo might be 20–40 persons smaller in the early season when project S-131 is in McMurdo and 170–340 persons smaller in the middle and late season, when projects S-116, S-145, and S-146 are in McMurdo. David Breshnahan, OPP, estimates that eliminating the long-duration balloon flights would reduce support staff at McMurdo by about 40 people (personal communication from Allison Cook, NSF, to J. T. Ensminger, ORNL, June 20, 1994). Breshnahan's estimate suggests that S-131 requires only about 10 people at McMurdo and S-116, S-145, and S-146 require about 80 people at McMurdo.

4. MINIMIZING THE IMPACTS OF BALLOON USE

As described above, balloon use by the USAP and other nations may be causing adverse impacts to several valued resources. Minimizing these impacts is desirable to help achieve the purposes of the Protocol and may improve the effectiveness of the program. This section identifies and discusses several alternatives for minimizing impacts from balloon use in Antarctica. The intent of this section is to explore a wide range of alternatives. Several alternatives may be infeasible. Others may be undesirable in light of program goals.

4.1 CHANGE BALLOON AND PAYLOAD MATERIALS

Balloons and payloads that find their way into the ocean pose a hazard to marine organisms, particularly whales (Sect. 3.2). For balloons much of the hazard is related to the expanse of plastic that may be floating at the ocean surface. One way to minimize this hazard is to make balloons, lines, and parachutes of materials that rapidly disintegrate or degrade in the ocean. Neoprene, polyethylene, and nylon are good choices from an engineering perspective because they are all relatively resistant to decay. However, their resistance to decay makes them more hazardous to marine organisms. In addition, balloon membranes are formulated by their manufacturers with stabilizers, antioxidants, and UV inhibitors. Except for long-duration balloon flights, balloon flights seldom exceed 2 h. A 2-h flight time is almost certainly too short a time for the stabilizers, antioxidants, and UV inhibitors in the membranes to have a significant effect of the usefulness on the balloon. On the other hand, these life extenders may increase the hazard the balloons pose for marine organisms by allowing these materials to persist longer in the ocean.

One potential mitigation would be to work with balloon manufacturers to develop balloon membranes, shrouds and parachutes for use in Antarctica that do not have stabilizers or that include additives that shorten the balloon life so they deteriorate quickly under antarctic conditions. Both increased UV light sensitivity and moisture sensitivity might be effective. Balloons may spend one or more seasons on the surface before being buried by snow or blown into the ocean. Increased UV sensitivity could accelerate balloon deterioration so they are less hazardous when they reach the sea.

An even more desirable trait for balloon material trait would be instability in the presence of water or salt water. Antarctica is an extremely dry environment. High absolute humidities normally occur only near the open ocean and in occupied buildings. If a balloon membrane material could be formulated that would remain stable in the air but deteriorate after a few days in the ocean, the hazard to marine organisms could be lessened or eliminated. Such a material might also be used for the very large long-duration balloons.

The Protocol prohibits disposal of polystyrene foam in Antarctica. Because the rawinsonde and ozonesonde enclosures are made of polystyrene foam, the balloon program incidentally involves polystyrene foam disposal in Antarctica. Also, as the foam is broken into small pieces, it may become a hazard to birds that might ingest it (Sect. 3.2.3). Sonde enclosures might be made from other materials. An example of a material that might be suitable is the kind of paperboard that is used to make egg cartons. This material appears to be rigid, is strong enough to contain the sonde instruments, has some insulation value (for keeping the enclosed instruments warm), and would deteriorate much more quickly in the ocean than polystyrene foam. Other materials that have similar or better environmental characteristics may be available.

Ice may be a suitable substitute for steel pellets or soil used as ballast in long-duration balloon flights. Either natural ice mined near McMurdo or distilled water ice would have much less potential for contamination of antarctic soils, snow, and ice than steel pellets or soil. Equipment for dropping ice ballast may be more bulky than the equipment used to drop steel pellets because of low density of the ice, but if ice pellets can be kept from melting into large chunks it may not need to be heavier.

Another approach would be to use compressed helium to replace helium that leaks from the balloon instead of dropping ballast. Helium can lift about 5 times its mass so a system that contained about 50 kg (100 lb) of compressed helium and weighed no more than about 270 kg (600 lb) could substitute for a system that uses 230 kg (500 lb) of ballast. The cylinders used to contain compressed helium are much heavier than the helium they contain so it may not be possible to develop such a system. On the other hand, steel pellets are inexpensive and in most parts of the world dropping them might cause no impact of concern, so it may be that such a system is feasible but has not been developed because there has been no need for it.

4.2 MINIMIZE BALLOON USE

Balloons are flown in Antarctica for several very good reasons outlined in Sects. 2.1 and 5. Minimizing balloon use would inevitably lead to some loss of the values for which balloons are used. This section explores options for reducing balloon use and the benefits and impacts that might result from doing so. The options discussed below would require more study than was within the scope of this effort before they were pursued.

4.2.1 Terminate Scientific Uses of Balloons

If scientific uses of balloons by the USAP were terminated, all flights of ozonesondes and long-duration balloons would be eliminated. Flights of rawinsondes would be reduced. Rawinsondes would continue to be flown during aircraft operations, but they would no longer be flown at other times. At McMurdo, balloons would be flown twice per day from about September 20 until about February 20 each austral summer for a total of about 320 balloon launches per year. The South Pole Station is open for LC-130 flights from about October 20 through February 10 during each austral summer. With two flights per day during the open period, about 250 weather balloons would be launched each year, about half the current number.

In total, over half the USAP balloon flights would be eliminated. This reduction would reduce impacts on wilderness and aesthetic values by about half, and approximately half the potential for impact to rare and unique areas would be eliminated. The potential impact to endangered whale species is due to the cumulative effect of all nations flying rawinsondes and other balloons in Antarctica. The USAP contribution is on the order of 5% of the total; halving the number of balloons flown from McMurdo would reduce the USAP contribution to between 2% and 3%.

The logistical effects of reducing balloon flights could be substantial. The number of people deployed at McMurdo could be reduced by between 80 and 340 during the long-duration balloon flights. Most of the balloon-related cargo shipped to McMurdo would be eliminated. The number of LC-130 flights to the South Pole Station needed to support balloon flights would be reduced from over 3/year to about 1/year (assuming that half of the rawinsonde flights are for scientific purposes). The need for up to 70 LC-130 hours to support the long-duration balloon flights would be eliminated, and the need for one or more LC-130 flights from New Zealand to McMurdo could be eliminated by not deploying the long-duration balloon activities.

The adverse effects on scientific research would also be substantial. Eliminating rawinsonde flights from the austral winter could reduce the quality of weather predictions in the southern hemisphere and eliminate a source of information about the circulation of the atmosphere over Antarctica. Elimination of ozonesonde flights eliminate an important source of information about the behavior of the stratospheric ozone layer over Antarctica. Long-duration balloon flights provide astrophysical information at lower costs than by space flight, the prime alternative.

4.2.2 Reduce Use of Rawinsondes flown to Support Air Operations

Rawinsondes are flown twice a day during air operations periods to provide current weather information for flights. However, during normal periods when many flights are beginning and ending at McMurdo and the South Pole stations, the best weather information may come from the pilots of earlier flights, and data from the second rawinsonde flight of the day may be unnecessary. Launching a second rawinsonde only on days when an aircraft flight is to be initiated more than 14 hours after both the last balloon flight and the most recent flight into or out of the station would substantially reduce the number of balloon flights. Adopting this protocol would reduce the number of rawinsonde flights from the South Pole Station by about 100/year and reduce the number from McMurdo by about 150/year.

This alternative would reduce the impacts of balloon flights somewhat less than eliminating scientific balloon uses, but it would have no adverse impacts on science and might have no more than minimal impacts on flight safety.

4.2.3 Maximize Use of Balloon Launches

There are opportunities for one balloon to carry two or more payloads thereby reducing the number of balloons flown. Rawinsondes are light [220 g (0.5 lb)] and can be carried by every balloon flown in Antarctica. Approximately 75 ozonesondes are flown from the South Pole Station each year. In nearly every case, the ozonesonde balloon [usually 550-m^3 (19,000-ft^3 size] could easily carry the additional weight of a rawinsonde. If ozonesonde and rawinsonde flights were coordinated, the number of balloons launched from the Pole could be reduced by about 75 without any loss of the services rawinsondes provide. This has been done occasionally at the South Pole Station but it does not appear to be the usual practice.

Only about 40 ozonesondes are launched from McMurdo each year but using ozonesonde balloons to carry rawinsondes as well would reduce the number of weather balloons flown by about 6%.

4.3 MAXIMIZE RECOVERY OF BALLOONS AND PAYLOADS

Another option for reducing impacts of balloon operations would be to recover more of the balloons and payloads. Opportunities for recovery of balloons and their payloads are limited but may be more extensive than currently perceived. Because most of the adverse effects of balloon flights result from the accumulation of spent balloons and payloads in Antarctica, recovering some balloons and payloads could reduce those impacts.

Recovering balloons is a daunting task. For the 1992–93 field season, S-131 requested 36 helicopter hours plus Twin Otter support to recover high-value payloads from just 12 ozonesonde flights. Helicopter flights are costly and have environmental impacts of their own. A helicopter flight crew consists of 3 men and a typical flight day might consist of between 4 and 6 flight-hours. In addition there are maintenance and support personnel, which are assumed to consist of about 3 person-days per flight day. Thus, attempted recovery of 12 balloon payloads could require between 36 and 54 person-days of air support in Antarctica, not including Twin Otter support or science team personnel involved in recovery of the payloads. From this perspective, payloads must be very valuable to justify the expense of recovering them. Aircraft operations also have environmental impacts. Helicopters use about 270 kg (600 lb) of fuel per hour. They also tend to drip small amounts of hydraulic fluid almost everywhere they go. Support for personnel who operate and maintain helicopters contribute to the environmental effects of operating McMurdo Station.

The high-value payloads that project S-131 attempts to recover include global positioning system (GPS) devices to aid in their location. Rawinsondes and ozonesondes flown from McMurdo come down in a 60,000-km^2 area (23,000 $miles^2$) (Fig. 3) and balloons flown from the South Pole Station come down in a comparable area (Fig. 2). Rawinsondes and regular ozonesondes do not incorporate GPS devices, so finding them would require visual examination of very large geographical areas. Attempting to recover any substantial fraction of these balloons and payloads would appear to require a huge effort with environmental impacts that may be larger than those of leaving them.

Long-duration balloon payloads are usually recovered, but only recently has recovery of the balloons been contemplated (Sullivan and Needleman 1994). These balloons are very large. When they reach the ocean and especially when they break into smaller pieces, they could contribute to adverse effects on marine mammals. GPS devices, such as those used on high-value ozonesondes, could also be used with the high-altitude, long-duration balloons. These GPS devices could be attached to the balloons and used to pinpoint the position of balloon's transmitter. Balloons that fell in areas where recovery is feasible could be recovered.

Adding a separate parachute to the balloon (in addition to the parachute for the gondola) might also increase balloon recoveries, but it may not be feasible because the added weight of the parachute. If the balloon and gondola fall at similar velocities, then the likelihood of the balloon landing near the gondola is increased and the chances of recovery are enhanced. Because of the very large size of the balloons, handling and transporting them remains a significant challenge even after the balloon is found. A specially equipped LC-130 or helicopter may be needed to recover one of these balloons because of their very large size. Because the balloons weigh more than 1600 kg (3500 lb) and the maximum payload of HH-1N helicopters used by the USAP is only 900 kg (2000 lb), the balloons would have to be cut into two or more pieces and recovered in multiple helicopter flights (USAP 1992). The environmental costs of recovering these very large balloons may outweigh the potential benefits. In addition, spending aircraft or helicopter time recovering balloons and payloads would reduce the support available for other scientific activities.

4.4 REMOTE SENSING

There are a number of remote sensing techniques that can provide some but not all of the information provided by rawinsondes and ozonesondes. One alternative is ground based remote sensing using radar or lasers. Bernard Lettau (NSF, OPP, personal communication to Lance McCold, ORNL, June 29, 1993) has indicated that these systems are more complex than balloon soundings, would require more people, and are not as reliable. He also reported that the National Center for Atmospheric Research (NCAR), Boulder, Colorado is developing remote sensing systems.

Satellites are currently used to measure the total ozone in the atmosphere, but they cannot give the ozone concentrations at different altitudes which are needed to understand the behavior of stratospheric ozone. Lettau reports that satellites are theoretically capable of resolving temperature profiles in the atmosphere but do not hold any prospect for measuring wind velocities.

As long as the receiving station is built elsewhere, satellite-based remote sensing would have no environmental impact on Antarctica, but does not appear to be capable of providing the data needed for aircraft safety or for stratospheric ozone research. Ground-based remote sensing appears to have the potential to replace weather balloons in the future but is not presently capable of doing so. The reported complexity of these systems suggests that they would have appreciable indirect environmental effects due to the people and materials needed to operate them. There is insufficient information available at this time to assess the magnitude of these indirect environmental effects. The current system of rawinsonde use has larger logistical impacts than are at first apparent, so it is possible that a somewhat complex remote sensing system may have some latitude before its logistical impacts exceed those of balloon-borne sondes. Remote sensing appears to have the significant advantage that it does not require scattering spent balloons and payloads around the antarctic landscape.

4.5 REMOTELY PILOTED AIRCRAFT

Since 1988, the National Aeronautics and Space Administration (NASA) has flown ER-2 aircraft (modified U-2 spy planes) to altitudes of nearly 21,000 m (68,000 ft) above Antarctica to collect air samples. NASA is funding development of an unmanned aircraft, called Perseus, intended to be able to reach altitudes of 25,000 m (82,000 ft). This aircraft would require less logistical support than manned aircraft, but would seem to require much more support than a balloon. It would require about 45 kg (100 lb) of fuel and 140 kg (300 lb) of liquid oxygen for each flight. This aircraft would be launched like some sailplanes (i.e., pulled by a winch-wound cable until airborne). Once airborne, the cable would be detached and its motor would be engaged (Ashley 1992).

Aircraft generally operate below altitudes of 10,000 m (33,000 ft). A remotely- or automatically-piloted aircraft might be designed that is much less complex than the Perseus, if it were intended only to operate at altitudes up to 10,000 m. Such an aircraft might eliminate the need for the second daily rawinsonde that supports aircraft operations. The ideal platform to replace the second-daily rawinsondes during the austral summer would be solar powered and capable of staying aloft for months at a time. Such an aircraft could remain at altitudes above most clouds so it could operate on solar power almost full time. In order to provide data on atmospheric conditions at various altitudes, it might be programmed to descend from its maximum to its minimum altitude over a period of an hour or two before slowly returning to its maximum altitude. (To our knowledge such an aircraft does not now exist, but it may be technically less demanding than the Perseus aircraft.)

After reaching altitude, an automatically-piloted aircraft would probably require about the same ground support as rawinsondes or ozonesondes because, as with balloons, only a person to monitor tracking and data transmissions would be needed. The overall environmental effects of such aircraft would appear to be less than the effects of balloons—no balloons would be littered around the antarctic environment, helium cylinders would not need to be transported to and from McMurdo and South Pole stations, and the numbers of people involved may be smaller. On the other hand, remotely- and automatically-piloted aircraft like Perseus are only now in the development stage; a fuller understanding of these aircraft may show that they would have more serious impacts than balloon operations. In addition, solar-powered aircraft would not work during the austral night, when balloon flights would have to be resumed. Because most balloon flights occur during the austral summer, such an automatically-piloted aircraft could reduce the number of balloon launches from McMurdo and South Pole Stations by about two-thirds.

4.6 OTHER ALTERNATIVES

Sounding Rockets

Sounding rockets could deliver sondes to the appropriate altitudes for atmospheric measurements. Once at apogee, the sondes could measure conditions at various altitudes as they parachute to earth. The advantage of such a system is that it would eliminate the need for balloons and transport of helium cylinders. Like balloons, however, both rockets and payloads ultimately return to earth resulting in the unavoidable deposit of debris on the antarctic environment. (Recovering rockets might be an option but it would be unlikely to be implemented because nearly all current rockets are designed for a single use to minimize cost and weight.) Further, the logistical requirements of rocket launches could be even greater than those of balloons. Rocket propellants are hazardous, and great care would have to be taken in their handling; they would certainly present a greater hazard than balloons to the safety of personnel working with them. In addition, rocket motors would seem to present a new source of air pollution, both near the ground and at altitude. Care would have to be taken to assure that rocket motor exhaust would not cause false readings of instruments designed to measure ozone or particles in the stratosphere.

Remotely Piloted Dirigibles

Dirigibles could be used to gather atmospheric data from altitudes. They could remain aloft for extended times by proper engineering of the balloon membrane, and the could use solar energy to power propellers that maintain their positions relative to the ground. Because a major purpose of sondes is to sample atmospheric conditions at a range of altitudes, a serious problem with dirigibles would be their limited ability to change altitude. They also do not offer obvious environmental advantages over current practice because they would have to return to earth at intervals to refill their helium supply. Takeoffs and landings could be problematic at many times because of severe weather.

5. SCIENTIFIC BENEFITS AND ECONOMIC COSTS

While the principal focus of this report is the environmental effects of USAP balloon activities, a full picture of USAP balloon activities must include a brief explanation of the scientific value of the enterprise or the financial costs of the activity. What follows is clearly not an exhaustive treatment of either scientific importance of antarctic ballooning or the costs of the activities, but it is intended to give the reader a general understanding of these important considerations.

5.1 RAWINSONDES

Weather balloon data is useful for several scientific purposes. Vertical profiles of humidity have been used for estimating moisture budgets of the antarctic continent. Scientists have used rawinsonde data from stations around Antarctica to estimate the moisture flux from the continent and for research on relationships between large-scale atmospheric circulation features and katabatic winds (David Bromwich, Ohio State University, Columbus, Ohio, personal communication to Lance McCold, ORNL, Oak Ridge, Tennessee, September 21, 1993). Time-series analyses of the behavior of the circumpolar vortex may be useful in a variety of climate-change investigations, such as determining the influence of the strength and shape of the circumpolar vortex on the ozone hole. Studies of the trends in the heights of temperature inversions in antarctic air masses can be useful in detecting an anthropogenic component of the greenhouse effect.

Rawinsonde data collected at McMurdo and South Pole Stations are archived by the National Climatic Data Center (NCDC) in Asheville, North Carolina. Archived data were purchased in order to perform the analyses described elsewhere in this report. For the South Pole Station, rawinsonde data were sporadic. The best record was for 1985 with 206 usable ascents. The years 1986 and 1987 had 151 and 92 usable ascents, respectively. Other years had even more sporadic data. The McMurdo rawinsonde data is even more sparse. The year 1991 had the most usable data with just 91 ascents from the period February 1 through October 29. Searches of the data for several other years produced few usable data.

Our efforts to find the data through other sources were not successful. The NCAR apparently has the same data as archived by NCDC (William Spangler, NCAR, Boulder, Colorado, personal communication to T. J. Blasing, ORNL, October 1, 1993). The NSF has supported establishment of the Antarctic Meteorologic Research Center at the University of Wisconsin, Madison, under the auspices of Charles R. Stearns (S-283). The Center has not been archiving upper air data but will probably be asked to do so in the future (Bernard Lettau NSF, OPP, Washington, D.C., personal communication to Lance McCold, ORNL, Oak Ridge, Tennessee, October 1, 1993).

Rawinsonde data are broadcast on the "Global Telecommunications System," from which the data are downloaded and used for southern hemisphere weather predictions (David Bromwich, Ohio State University, Columbus, Ohio, personal communication to Lance McCold, ORNL, Oak Ridge, Tennessee, September 21, 1993). It was suggested that these data may also be downloaded and archived somewhere in the southern hemisphere, perhaps Australia. Efforts to find information about this possible source of rawinsonde data were not fruitful.

The South Pole Meteorology Program is operated by NSF's contractor ASA, while the McMurdo program is run by the Navy weather office in McMurdo. The NSF spends a substantial amount of money to launch antarctic rawinsondes. As shown by Table 4, the annual cost of materials and shipping for the USAP rawinsonde program is about $400,000. In addition to the materials costs of balloon flights, personnel are required for preparing, launching, and tracking the balloons as well as for managing the resulting meteorological data. An estimated 0.5 person-year per year is required for these activities at the South Pole Station, and about 1 person-year per year at McMurdo Station. These people also induce indirect costs to the program for food, shelter, heat, electricity, water, and waste management. With these indirect costs, the overall cost of the rawinsonde program may be between 1 and 2 million dollars per year.

5.2 OZONESONDES

The stratospheric ozone hole that forms annually over Antarctica is a focus of international concern and of scientific research. Project S-131 flies the ozonesondes from McMurdo. This project is intended to improve the understanding of the stratospheric clouds that form over Antarctica. Much of the ozone depletion is caused by the interaction of elemental chlorine with ozone. Polar stratospheric clouds appear to play a major role in the chemical reactions that liberate elemental chlorine from the hydrochloric acid and chlorine nitrate gases found in the stratosphere. Balloon-borne ozonesondes and particle detectors have been used to detect ozone depletion mediated by volcanic aerosols from the August 1991 eruption of Cerro Hudson (Deshler and Adriani 1993).

Table 4. Estimated material cost of the USAP rawinsonde activity

Material	Annual cost ($1,000)
McMurdo Station	
Balloons	42
Sondes	60
Helium	12
Helium rack leasing	55
Shipping	34
Subtotal	200[a]
South Pole Station	
Balloons	32
Sondes	46
Helium	12
Helium rack leasing	55
Shipping	68
Subtotal	210[a]
Total	420[a]

[a]Totals may not add due to rounding.

Ozonesondes and water vapor detectors are being flown from the South Pole Station by project S-257A. Measurement by ozonesondes with back-scatter sondes and frost-point sensors have shown that winter cooling causes dehydration and denitrification of the stratosphere as well as formation of stratospheric clouds (Rosen, et.al. 1992). Measurements by these instruments have been used to detect the correlation between formation of polar stratospheric clouds and ozone depletion (Rosen, et.al. 1993).

Recent funding for S-131 has been between $350,000 and $400,000 per year. Shipping and transportation between the home institution and Antarctica and all support supplied while in Antarctica represent additional costs for which estimates are not available but which may exceed the value of the grant by a large margin. For example, ozonesonde balloons are considerably larger than balloons used for rawinsondes, so we estimate that this project's balloons use one flat rack of helium at a cost of $6000. Transport of the flat rack between the United States and McMurdo may add another $16,000. Leasing one rack for about 20 months per fill adds $25,000 to $30,000 for a total annual cost between $400,000 and $450,000.

Project S-257A is a multi-aspect project, only part of which involves ozonesonde launches. About $80,000 of S-257A's grant purchases ozonesondes, balloons and other materials used for the ozonesonde launches. This amount includes all materials for ozonesondes except helium. Ozonesonde balloons are considerably larger than balloons used for rawinsondes and are estimated to use one flat rack of helium at a cost of $6000. Transport of the flat rack between McMurdo and the South Pole Station costs about $16,000, and transporting it between the United States and McMurdo may add another $16,000. Leasing the rack for 20 months per fill adds $25,000 to $30,000 for a total annual cost of about $150,000 for materials. The project fields a team of about six people including two who winter over at the South Pole. A quarter, perhaps less, of the time of the two winter-over personnel is used for ozonesonde launches (S.J. Oltamans, National Oceanic and Atmospheric Administration, Boulder, Colorado, personal communication to Lance McCold, ORNL, Oak Ridge, Tennessee, January 26, 1994).

5.3 HIGH-ALTITUDE, LONG-DURATION BALLOONING

High-altitude, long-duration ballooning (S-145) supports astrophysical and astronomy projects. During the 1992–93 season it supported the joint U.S.-Russian Long-Duration Antarctic Mars Calibration Balloon (LAMB) Mission (S-146) and a High Resolution Gamma-Ray and Hard X-Ray Spectrometer (S-116). During the 1993–94 season it supported two long-duration balloon flights for the Japanese/American Cosmic Ray Emulation Chamber Experiment (JACEE) (S-147). The JACEE project plans to launch 20 long-duration balloon flights over the next 10 years.

The objective of the LAMB project (S-146) was to verify and calibrate gamma-ray and neutron remote-sensing instruments that can be used to obtain geochemical maps of planetary bodies. The detectors were prototypes for those that will be used on U.S. and Russian planetary space missions and were used to measure how gamma rays and neutrons produced by cosmic rays interact with a simulated martian soil. Project S-116 measured gamma rays to learn about nuclear reactions within solar flares and the formation of heavy elements in Supernova 1987A. Study of solar flares and supernovas may lead to better understanding the origin and fate of the solar system. The goals of the JACEE project (S-147) are to measure the cosmic ray energy spectrum and composition in the ultra-high energy range and to study nuclear interactions at these energies.

Long-duration balloon flights are much less expensive than the space flights they replace, but their costs are substantial. Each balloon costs about $90,000, and each flight requires 4 half-racks of helium worth about $24,000. Because of the timing of the resupply ship, each rack of helium requires leasing a container for about 20 months at a cost of $25,000 to $30,000, so the costs of the major materials for two balloon flights total $430,000 to $500,000. Finally, the materials for launching 2 to 5 pathfinder balloons probably adds thousands of dollars to the cost.

Launching two balloons per year requires 15 personnel from the National Scientific Balloon Launch Facility to deploy to McMurdo for approximately the period November 20 through January 10. With travel time, preparations, etc., these personnel may spend 2.5–3 person-years on the launches. Project S-147 deploys four people to McMurdo for approximately the period November 28 through January 20. As noted in Sect. 3.8, the number of secondary personnel in McMurdo to support personnel associated with long-duration ballooning is between 70 and 170.

6. SUMMARY AND RECOMMENDATIONS

Section 3 shows that balloon use is having only very small, perhaps negligible, impacts to opportunities for future scientific research; birds, seals or benthic marine organisms; most SSSIs; historic sites and artifacts; antarctic soils, snow and ice; and human safety. For southern whales, the wilderness and aesthetic values of Antarctica, and possibly White Island or Cape Crozier SSSIs, the available information does not support a conclusion that the impacts are negligible. Balloon activities require a significant amount of logistical support and thus contribute to the environmental impacts of operations at McMurdo and South Pole stations.

Section 3.2 presents estimates that each year between 6 and 60% of the whales in the southern ocean may be encountering balloons that had been flown from antarctic stations. The probability that an encounter leads to a fatality is unknown, but even modest probabilities (e.g., 1:100) could lead to population-level effects. If balloons turn out to be very long lived in the ocean, the ultimate encounter rate may be even larger. These estimates are based on several plausible but uncertain assumptions. The available information cannot rule out the possibility that balloon launches from antarctic stations may, in combination with other human activities (e.g., trawling for kill), be retarding the recovery of endangered whale species of the southern ocean.

The environmental impact, however large, is the cumulative effect of all the balloons flown in Antarctica. If the United States stopped all balloon flights, the magnitude of the impact would decrease by only about 7% [McMurdo Station's part of the approximately 9000 balloons per year from all coastal antarctic stations (Sect. 2.2)]. These findings should be shared with the Parties to the Antarctic Treaty. Additional information they could provide should be used to refine the impact estimates presented in this report, and to develop strategies for minimizing the impacts balloons may be having. In addition, consultation with the NMFS, as required by Section 7 of the Endangered Species Act when an agency's action may adversely affect an endangered marine species should be considered.

Section 3.3 reports that balloons launched from the South Pole Station and probably those from McMurdo Station may be having impacts on the aesthetic and wilderness values of Antarctica in the areas near the stations. The impact results from the physical presence of the balloon. Only reducing the number of balloons that can be found by antarctic travelers will reduce the magnitude of the impact.

McMurdo and South Pole Stations are two of the USAP's major facilities. Each of these stations has significant environmental effects on their immediate vicinities. To a considerable extent the magnitude of their impacts are related to the number of people at the stations and activities that occur there. All balloon operations contribute to the stations' impacts. Rawinsonde launches make modest contributions to the numbers of people and support requirements at both stations, but these demands exist throughout the year. Ozonesonde launches at the South Pole Station are similar, but they require less support than rawinsonde launches because there are fewer of them. Ozonesonde launches at McMurdo occur during the austral spring, but during that time they are a moderate contributor to overall impact of the station. Long-duration balloon flights involve large numbers of people during December and January. At these times, the long-duration balloon flights are major contributors to the impacts of operating McMurdo Station.

Environmental impact assessments must often deal with considerable uncertainty. In Antarctica, the uncertainty is greater than usual, as the number of assumptions needed for the analyses in Sect. 3 suggests. This uncertainty is problematic whether it causes overestimates or underestimates of impacts. Overestimates may lead the NSF to take unnecessary actions to mitigate negligible impacts, and underestimates may discourage the NSF from taking needed mitigative actions. The most serious concern identified by this study is possible impacts to endangered whales due to ingestion of or entanglement in balloons. To resolve these uncertainties associated with this analysis, three kinds of information are needed: (1) the numbers, properties, and fates of balloons and payloads that are launched in Antarctica and enter the ocean; (2) the behavior and fate of floating balloon materials in the Antarctic ocean; and (3) the behavior and biology of the endangered southern whales.

The number, size distribution, and composition of balloons and their payloads launched throughout the antarctic region and the rapidity with which they enter antarctic seas are important in determining their cumulative effects. The assumptions used in this study regarding numbers and types of balloons launched around the continent are reasonable but actual numbers for non-USAP stations would improve the accuracy of the estimates.

The half-lives of the materials from which balloons and payloads are made are not known for either the temperate oceans or the extreme conditions prevailing in antarctic oceans. Moreover, as balloon and package materials slowly degrade under the influence of weather, sun, and biological activity, the potential hazards for marine animals may worsen for a time as greater numbers of (smaller) pieces of material are generated. It is also not known whether the neoprene balloons will sink shortly after entering the sea or whether entrapped gas, released by colonizing algae, and the attached foam instrument package may keep them afloat indefinitely. Polyethylene, on the other hand, may sink if colonized by organisms, such as crustaceans, that are heavier than water, however, subsequent decolonization can allow the plastic material to resurface.

This study assumed that balloons are randomly distributed throughout the Ross Sea for the assessment of McMurdo-launched balloons and throughout the entire southern ocean for assessment of the cumulative impacts of all antarctic balloon operations. If drifting balloons accumulate in areas in the southern ocean that coincide with important feeding areas, the impacts could be greater than estimated (Sect. 3.2.3). Plastic debris has often been observed to aggregate in windrows and other convergence areas coincident with potential prey items. In this regard, right whales have been observed to feed on food and anything else entrained in a convergence area (Goodyear, J., University of British Columbia, Victoria, British Columbia, personal communication to G. K. Eddlemon, ORNL, October 27, 1993). If balloons accumulate in whale feeding areas, the balloon encounter rate (thus ingestion and envelopment rates) would be considerably higher than calculated in Sect. 3.2. On the other hand, balloons may aggregate in little used areas of the southern ocean and thus lead to lower encounter rates. Balloon materials may also collect in or near areas along the coasts and among the sea ice important to feeding or breeding of seals and seabirds, where such materials could represent serious hazards to these animals. Research is needed to determine where balloons accumulate and where whales concentrate their feeding.

Population sizes, dynamics, and distribution of the great whales are poorly known. Available information suggests that several southern whales have critically low populations and that there is no evidence of significant recovery. Evidence that whale numbers are rebounding would do much to allay the concern on which the conclusions of Sect. 3.2 are based. Additional information about whale behavior in relation to balloons is needed to determine whether or not balloons are having a significant adverse impact on endangered whale species. The needed information includes: long-term average cruising speed of the various whale species, the fraction of time whales spend inactive or below the surface of the sea (precluding contact with floating balloons), the behavior of whales when encountering balloon material (e.g., are they attracted to balloon materials or do they avoid them, do they ingest or become entangled in them), and the similarity (if any) of the echo-location signatures of balloon materials to the signatures of prey as perceived by whales.

Estimates of the magnitude of the logistical impacts of balloon activities are based on a general understanding of operations at McMurdo and South Pole stations. More precise estimates require a more precise understanding of the logistical demands different activities place on the stations. Each person living at a station requires certain amounts of food, water, heat, electricity, and etc. A thorough knowledge of the relationship between the number of people, their activities, and logistical support needed at the stations is needed to accurately forecast the impacts of science, construction, and other activities. A model of logistical requirements that will allow accurate forecasts of any activity's direct and indirect logistical requirements should be developed and maintained. Such a model would allow more accurate forecasts of indirect environmental impacts of proposed activities, accurate estimation of the full economic cost of proposed science and other projects, and improved logistical planning.

Section 4 discusses a number of alternatives and mitigation measures for reducing the impacts of balloon activities. Substituting less stable materials for the plastic balloons and polystyrene foam sonde enclosures could reduce the hazard to marine organisms (Sect. 4.1). Research and development on these possibilities may be needed, but materials with better environmental characteristics could have benefits far beyond the USAP. Balloon and sonde materials that are less hazardous to the environment can be expected to be adopted by other nations using balloons in Antarctica. In addition, plastic in the ocean is also a concern in temperate regions. Though weather balloons have not been identified as a major contributor to plastic pollution in temperate oceans, the general concern about plastics in the ocean could lead to adoption of replacement materials for rawinsondes if they became available. Use of steel pellets or soil for ballast would be of little concern in most parts of the earth. The international communities' desire to maintain Antarctica in a pristine state suggests that other means of controlling long-duration balloon altitude may deserve consideration.

The most immediate way to reduce the environmental impacts of balloon operations would be to reduce the number of balloons launched. Eliminating balloons launched for scientific purposes would significantly reduce the numbers launched by the United States, but would have severe adverse impacts on valuable science activities. Reducing the frequency of balloon launches flown in support of air operations would produce a modest reduction in impacts, but it is not clear whether safety could be assured. The feasibility of reducing the frequency of balloon flights in support of air operations as suggested in Sect. 4.2.2 should be evaluated. If it is feasible, it would be the easiest way to reduce balloon impacts. Rawinsonde and ozonesonde flights should be coordinated so that the number of balloon flights could be minimized as suggested in Sect. 4.2.3.

Collecting upper air data by remote sensing appears to hold the potential to eliminate many of the environmental impacts associated with balloon flights (Sect. 4.4). However, while it is clear that the impacts of such systems would be different than those of balloon flights, it is not clear that they would be smaller or less important overall.

Remotely-piloted aircraft are presently under development that may be capable of replacing some balloon flights while offering other advantages (Sect. 4.5). NASA is supporting development of these aircraft with cooperation from the USAP. These aircraft might have smaller impacts than balloon operation, but it is also possible that their overall impacts could be greater than balloon operations.

Recovering balloons and low-value payloads would reduce impacts of balloon activities, but doing so would have very high logistical costs as well as possibly large environmental impacts (Sect. 4.3). Section 4.6 examined sounding rockets and remotely-piloted dirigibles as alternatives for collecting data currently gathered by balloon flights; neither appears to be attractive from an environmental perspective.

Rawinsonde, ozonesonde, and long-duration balloon flights serve important scientific purposes (Sect. 5). Rawinsonde data are useful for efforts to understand global atmospheric circulation, antarctic weather patterns, and global climate change. Ozonesonde data are important in ongoing efforts to measure and understand stratospheric ozone depletion. Long-duration balloon flights are a less expensive alternative to space flights for certain astrophysical studies.

The materials cost of the rawinsonde program is estimated to be on the order of $400,000/year. With labor and indirect costs it may run as high as $2 million/year. Materials and grants costs of ozonesondes launched by the USAP appear to be on the order of $600,000/year; with labor and indirect costs, the total cost of ozonesonde launches may be much more. The materials costs of two long-duration balloon launches per year are on the order of $500,000. Grant funds to S-147 and travel expenses for S-145 and S-147 personnel may bring the total direct costs to the order of $1 million per year. Indirect costs of supporting these activities may be greater than the direct cost. In addition, NASA provides major support to the long-duration balloon flights, including the salaries of the 15 personnel from the National Scientific Balloon Launch Facility.

The scientific value of rawinsonde data is apparently not being realized because archiving problems have made most of the data collected by the USAP essentially unavailable to researchers (Sect. 5). The data archived at the NCDC are sparse and sporadic. Steps should be taken to see that the quality and availability of future data is assured. The feasibility and desirability of attempting to salvage some of the existing data should also be considered. Excellent recent rawinsonde data from the South Pole Station were provided by the USAP's contractor, ASA. The Navy was unable to provide comparable data for McMurdo Station because it retains no copies of the data and NCDC had not processed the data due to funding difficulties. Until the archive situation is improved, arrangements should be made for ASA to archive the rawinsonde that data the Navy collects at McMurdo, along with the data collected at the South Pole. In addition, arrangements should be made to have the quality of rawinsonde data collected by the program assured before it is archived. Finally, the rawinsonde data collected by other nations operating in Antarctica should be acquired and archived so that it will be available to researchers in the United States and other nations.

7. LITERATURE CITED

Antarctic Support Associates (ASA) 1992. *United States Antarctic Program Science Program Plan 1992-1993*. Science Support Division.

Azzarello, M. Y., and E. S. Van Vleet. 1987. Marine Birds and Plastic Pollution. In: *Marine Ecology—Progress Series*, Vol 37:295-303.

Ryan, P. G. 1988. Concern About Plastic Pollution in Southern Ocean Seabirds. In:*Cormorant* , Vol. 16, No. 1, pp. 1–2.

Cundell, A. M. 1974. Plastics in the Marine Environment. In: *Environmental Conservation*, Vol. 1, No. 1:63–68.

Dean, J. A. (ed). 1973. Lange's Handbook of Chemistry. McGraw-Hill Book Co. New York.

Deshler, T. A. and A. Adriani 1993. Volcanic Aerosol and Ozone Depletion within the Antarctic Polar Vortex During the Austral Spring of 1991. *Antarctic Journal of the United States*, Volume XXVII—No. 5, pp. 274–275.

Division of Polar Programs 1992. *United States Antarctic Program Personnel Manual, 1992 edition,* National Science Foundation, Washington, D.C.

Ejiri, M., A. Kadokura, T. Hirasawa, N. Sato, R. Fyjii, H. Miyaoka, J. Nisimura, N. Yajima, T. Yamagami, S. Kokubun, H. Fukunishi, M. Yamanaka, and M. Kodama. 1993. Polar Patrol Balloon Experiment in Antarctica, *Advances in Space Research*, Vol. 13, No. 2, pp (2)127–(2)130.

Fowler, C. W. 1987. Marine Debris and Northern Fur Seals: A Case Study. In: *Marine Pollution Bulletin*, Vol. 18:6B, pp. 326–335.

Furness, B. 1983. Plastic Particles in Three Procellariiform Seabirds from the Benguela Current, South Africa. In: *Marine Pollution Bulletin,* Vol. 14, No. 8:307–308.

Joyner, C. C., and S. Frew. 1991. Plastic Pollution in the Marine Environment. In: *Ocean Development and International Law*, Vol. 22:33–69.

National Research Council (NRC) 1993. *Science and Stewardship in the Antarctic.* Committee on Antarctic Policy and Science; Polar Research Board; Commission on Geosciences, Environment, and Resources; National Academy Press, Washington, D.C.

National Science Foundation (NSF) 1991. *Final Supplemental Environmental Impact Statement for the United States Antarctic Program.* Office of Polar Programs, Washington D.C., October.

O'Hara, K. J. 1988. Plastic Debris and Its Effects on Marine Wildlife. In: *Audubon Wildlife Report 1988/1989*. pp. 395–434. W.J. Chandler, ed. Academic Press, Inc., New York.

Rosen, J. M., N. T. Kjome, and S. J. Oltamans 1992. A Study of Polar Stratospheric Clouds at the South Pole. *Antarctic Journal of the United States*, Volume XXVI—No. 5, pp. 244–245.

Rosen, J. M., N. T. Kjome, and S. J. Oltamans 1993. Simultaneous Ozone and Polar Stratospheric Cloud Observations at Amundsen-Scott South Pole Station during winter and spring 1991. *Antarctic Journal of the United States*, Volume XXVII—No. 5, pp. 279–280.

Sulivan, Cornelius W., and Harvey C. Needleman 1994. *Finding of No Significant and Not More than Minor or Transition Effect, Environmental Assessment, and Initial Environmental Evaluation; Management of Long Duration, Heavy-Lift Balloon Flights in Antarctica.* Office of Polar Programs, National Science Foundation, Arlington, Virginia, November 22.

United Kingdom, Italian and Korean observers, undated. *Report of a Joint Inspection Under Article VII of the Antarctic Treaty, January-February 1993.* Foreign and Commonwealth Office, London, Ministry of Foreign Affairs, Rome, Ministry of Foreign Affairs, Seoul.

United States Antarctic Program (USAP) 1992. *Helicopter Operations and Safety Guide,* National Science Foundation, August.

APPENDIX A

ESTIMATING WEATHER BALLOON LANDING LOCATIONS

Predictions of balloon landing locations were used to estimate the likelihood of balloons landing in sensitive areas near McMurdo Station, and the likelihood of impacts to aesthetic and wilderness values on the Polar Plateau near the South Pole Station. The locations at which balloons land are a function of the wind regime through which they ascend and descend and the duration of the flight. The duration of the flight is determined by the altitude at which the balloon bursts. Neoprene balloons are designed to stretch far beyond their initial volumes before bursting, but their ability to stretch diminishes at low ambient temperatures. Polyethylene balloons have little ability to stretch, so they are inflated to a small fraction of their maximum volume at launch. As they rise and the ambient pressure declines, their volumes increase until they burst when the volume of the helium, at the ambient pressure, exceeds the capability of the balloon. Generally, polyethylene balloons are used to reach greater altitudes, but at moderate ambient temperatures the 650-g (23-oz) neoprene balloons are capable of carrying rawinsondes to the same altitudes as the 200-m^3 (7000-ft^3) polyethylene balloons.

Among other measurements, rawinsonde data include wind velocities and balloon altitudes at 1-min intervals. This data was used to calculate a trajectory for each balloon. The horizontal distance travelled was estimated to be the product of the time between measurements (1 min) and the average wind velocity for the interval (one-half the vector sum of the wind velocities at the beginning and end of the periods). The record ends when the balloon bursts and begins to fall. We assumed that the balloon fell at twice the speed of ascent and moved through the same wind field through which it had risen; thus, the landing site was estimated to be in the same direction as the balloon location at the end of its recorded flight but half again as far from the launch point.

We used archived rawinsonde data to estimate the distribution of balloon landing sites. For the South Pole Station we used data from July 1992 through June 1993 supplied by John Gress of Antarctic Support Associates (ASA). The quality of this data was very good and provided just over 500 observations as shown on Fig. 2.

The U.S. Navy is responsible for rawinsonde data collected at McMurdo but was unable to provide it because the data had already been transferred to the National Climatic Data Center (NCDC). The antarctic rawinsonde data archived by NCDC is of poor quality. The best set of records for McMurdo that could be extracted from the archived data was for 1991. There were 91 usable records from the period February 1 through October 29. The small number of records and the lack of any records from the austral summer placed the representativeness of this data in question but no other source was available. We considered synthesizing a "typical year," but it was not possible because of the poor quality of records from other years.

The distribution of balloons shown in Fig. 2 was the basis for the estimate of the likelihood of travelers encountering a spent rawinsonde or ozonesonde while skiing to and from the South Pole Station (Sect. 3.3). Estimating the likelihood of a balloon landing in a sensitive area near McMurdo Station required a few more steps. We defined rings [each 25 km (16 miles) larger than the previous one] and sectors around McMurdo as shown in Fig. A.1. The sector boundaries are aligned with the cardinal directions, and the number of sectors was chosen to keep the area of each sector as close to the area of the inner ring as possible.

The number of balloon landings in each sector (estimated as described above) was used to calculate a probability of balloon per unit area by multiplying the number of balloon landings by the ratio of 650:91 (actual annual rawinsonde launches to number in the data set), and divided by the area of the sector. With these probabilities per unit area, the probability of a balloon landing on a sensitive area in the sector could be estimated by multiplying the land area of the sensitive area by the sector's probability per unit area.

As Fig. A.1 shows, the estimated balloon landing sites are far from equally distributed among the sectors, and the number of estimated landing sites within some of the sectors is small or zero. Such small (or zero) sample sizes lead to large uncertainty in the estimated probability of a balloon landing within a unit area of a sector. To attempt to characterize these uncertainties, we calculated the probability of a balloon landing in a sensitive area as if the sensitive area were located in each of the sectors adjacent to that in which it is actually located. The highest and lowest nonzero probabilities thus calculated (one probability for each adjacent sector) were used to establish the range reported in Sect. 3. This method appears to characterize the uncertainty reasonably well. However, an added source of uncertainty is that the summer season is not represented in the data. Wind patterns during the austral summer may be significantly different than at other times of the years, but the absence of data makes that impossible to determine.

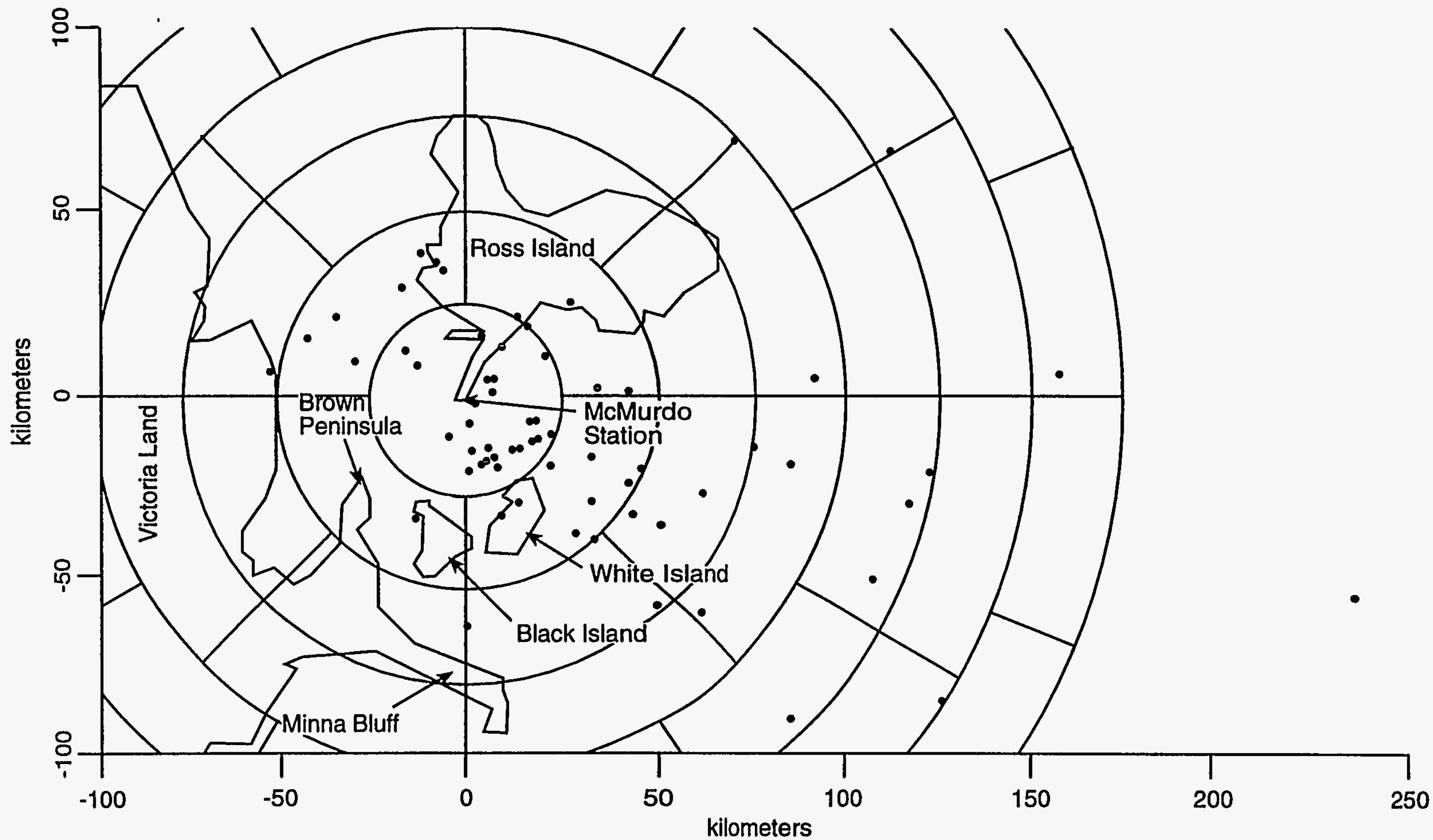

Fig. A.1. Approximate landing sites of 91 rawinsondes launched from McMurdo Station and sectors used to estimate the probability of landings in sensitive areas. (Position 0,0 is located at McMurdo Station.)

APPENDIX B
ANTARCTIC BIOTA

B.1 TERRESTRIAL ENVIRONMENT

Few environments anywhere on earth are less favorable for terrestrial life than Antarctica. More than 97% of the continent is permanently covered by ice and snow. Strong winds, lack of moisture, low temperatures, and salt accumulations inhibit growth. Distinct differences, however, exist between the extremely sparse ecosystems of the continent and the somewhat more varied biota of the Antarctic Peninsula.

The vegetation of the antarctic continent consists of only a few small and more primitive forms of plant life—algae, fungi, lichens, mosses, and rare liverworts. The animals that consume these plants and are sheltered by them are all very small invertebrates, the largest being less than 4 mm (1/6 in.) long. The major animal groups that have been identified among the low-growing antarctic vegetation include one-celled protozoans, several kinds of flatworms and roundworms, rotifers, tardigrades, insects, springtails, and mites (Walton 1987, Sømme 1985). About half of the terrestrial arthropod species (insects and mites) are actually parasitic on birds or seals. Both birds, such as penguins and petrels, and seals can be found on land, particularly during the breeding season; however, they depend on the ocean for their food. With the exception of those few birds that prey on other birds' eggs and young, most bird and seal species spend the majority of their time either on the sea ice or in the water. During the breeding season, it is not unusual for bird rookeries to occupy all snow-free level ground in many coastal areas.

The vegetation of the Antarctic Peninsula and its associated islands is subject to somewhat less extreme temperatures and receives more moisture. As a result, peninsular vegetation is more widespread and more varied than that in continental Antarctica. Generally, the species diversity is higher and the communities are more complex. In addition to algae, fungi, lichens, mosses, and liverworts, a few flowering plants can be found in the tundra-like vegetation of the Antarctic Peninsula and islands. Land animals include the same types of small invertebrates found on the continent. As on the continent, birds and seals may be found on coastal lands in abundance during the breeding season.

B.2 INLAND AQUATIC ENVIRONMENTS

Along the coasts in summer, meltwaters often form puddles, ponds, and lakes which vary widely in their physical and chemical characteristics and provide diverse ecosystems. These water bodies usually contain algae, bacteria, fungi, protozoa, and a few invertebrates. In lakes that freeze solid in winter, algae tend to form spherical clumps. Lakes that do not freeze completely contain planktonic algae, as well as dense growths of blue-green algae lining the bottom.

Some of the large lakes in the Dry Valleys of southern Victoria Land contain under their frozen surfaces several types of algae, including planktonic algae and periphyton. Associated organisms include bacteria, fungi, protozoa, rotifers, nematodes, and tardigrades.

B.3 MARINE ENVIRONMENT

Those areas of the Pacific, Atlantic, and Indian Oceans south of the Antarctic Convergence, a circumpolar boundary where cold waters of the Antarctic slide beneath the warmer waters of temperate latitudes, are often referred to as the southern or antarctic ocean. This area of nearly 3.0×10^7 km^2 represents approximately 10% of the worlds seas. With the exception of a roughly 10–50 km-wide, west-flowing coastal current called the East Wind Drift, most of the southern ocean from bottom to surface flows eastward at an average velocity in the range of 20–50 cm/s in the world's largest oceanic current, the Antarctic Circumpolar Current, also known as the West Wind Drift. The name given to the boundary between these two currents is the Antarctic Divergence, an important zone of upwelling, nutrient-laden waters.

Algal blooms in the nutrient-rich seas around Antarctica provide food for zooplankton, in particular, copepods, and kill. The kill, frequently found in great swarms, are a major food source for fish, squid, whales, seals, and certain birds, particularly penguins. The benthic communities below the level of ice scour exhibit remarkable species richness and stability and high biomass (Picken 1985). Benthic invertebrates, including sponges, corals, gorgonians, anemones, mollusks, crustaceans, and starfish are widespread and may be important contributors to the antarctic marine food web. Nearly 200 species of fish, such as antarctic cod, are important components of the food web.

About 50 species of birds, of which penguins are the dominant group, feed on marine life but breed on the coasts of Antarctica and its offshore islands. Adelie and Emperor penguins breed in regions of Antarctica only. Adelie penguins breed on ice-free pebble beaches during the short antarctic summer. In winter they stay near the edge of the pack ice, where their main food supply of kill is abundant. Emperor penguins generally breed on ice shelves attached to land. The chicks hatch during the winter and become independent in early summer when their food supply is most abundant.

Table B.1 lists the six seal species of the antarctic and their approximate total numbers. Four species are associated with the antarctic pack ice—the crabeater, Weddell, leopard, and Ross seals. Two other species, the southern elephant seal and the antarctic fur seal, are found on islands in lower latitudes north and south of the Antarctic Convergence. All species appear to have fairly stable, if not slightly increasing, populations. In the vicinity of McMurdo Station, Weddell seals predominate. Weddell pups are born on the pack ice in October and early November. Both cows and their pups remain on the ice until weaning occurs approximately 8 weeks later. Temperatures normally increase enough by February to cause the pack ice to melt, break up, and float away. Killer whales, which feed on seals and penguins, then enter McMurdo Sound until the temperature decreases and the sound refreezes.

Table B.1. Seals of the southern ocean.

Common name	Scientific name	Population[a] (thousands)
Seals	*Pinnipedia*	18,000–33,000
Crabeater seal	*Lobodon carcinophagus*	15,000–30,000
Weddell seal	*Leptonychotes weddellii*	800
Ross seal	*Ommatophoca rossii*	220
Leopard seal	*Hydrurga leptonyx*	220–440
Antarctic fur seal	*Arctocephalus gazella*	930
Southern elephant seal	*Mirounga leonina*	750

[a]Croxall (1987).

In addition to killer whales, several other whale species make summer feeding visits to antarctic waters (Table B.2). These include sperm whales and the baleen whales, in particular the fin, blue, sei, humpback, right, and minke whales. Smaller toothed cetaceans such as the southern bottlenose and beaked whales also occur in antarctic waters. Most whale species exhibit circumpolar distributions. The sperm, fin, blue, sei, right, and humpback whales are listed by the National Marine Fisheries Service as endangered under the Endangered Species Act of 1973.

Table B.2. Cetaceans of the southern ocean

Common name	Scientific name	Initial population[a] (thousands)	Current population[a] (thousands)	Status[b]
Baleen whales	*Mysticetes*			
Blue whale	*Balaenoptera musculus*	150–230	1–12	E
Fin whale	*Balaenoptera physalus*	400–490	70–125	E
Sei whale	*Balaenoptera borealis*	200	12–75	E
Minke whale	*Balaenoptera acutorostrata*	300–440	290–320	N
Humpback whale	*Megaptera novaeangliae*	100	2–3	E
Right whale	*Balaena glacialis*	100–300	3–4	E
Toothed cetaceans	*Odontocetes*			
Sperm whale	*Physeter macrocephalus*	1200	750	E
Arnoux's beaked whale	*Berardius arnuxii*	na	na	N
Southern bottlenose whale	*Hyperoodon planifrons*	na	na	N
Killer whale	*Orcinus orca*	na	na	N
Long-finned pilot whale	*Globicephala melaena*	na	na	N
Hourglass dolphin	*Lagorhynchus cruciger*	na	na	N
Commerson's dolphin	*Cephalorhynchus commersonii*	na	na	N
Spectacled porpoise	*Phocoena dioptrica*	na	na	N

[a]Populations in the southern ocean/hemisphere; World Wildlife Fund (1990), Chapman (1988), Gambell (1987), Brown and Lockyer (1984), Braham (1984); na = not available.
[b]Status under the Endangered Species Act: E = listed as endangered; N = not listed.

Most species of the larger whales have suffered precipitous population declines worldwide over the last few decades, primarily from overharvesting by man. Although population estimates vary widely, the blue whale, for example, has been reported to have declined worldwide from approximately 230,000 individuals to possibly fewer than 1000 (or up to 12,000, depending on the source). Of all the great whales, blue whales generally migrate the furthest south (along with the much smaller and more numerous minke whales), moving right up to and in among the pack ice, or near the coast itself if kill is accessible (Mizroch *et al.* 1984a; Chapman 1988; Fifield 1987). Kill comprise virtually the entire diet of blue whales, which feed on and near the surface by lunging forth with huge, wide-open mouths in the midst of kill swarms. Fin whales also penetrate far south into antarctic waters to feed on kill and other crustaceans but generally not as far as blue whales. Their numbers in the southern hemisphere (where a large majority of the world's total numbers reside) were reported to have declined from about 400,000 before exploitation, to somewhere in the range of 70,000–85,000 (Mizroch *et al.* 1984b; Chapman 1988).

The third largest baleen whale, the sei whale, occasionally grazes at very high latitudes near the edge of the pack ice but normally occurs between 40 and 50° S during the austral summer. Copepods and, secondarily, kill are their preferred prey (Mizroch et al. 1984c). Population estimates for sei whales vary greatly; one source estimates an initial southern population of 64,000 and a post-exploitation population of less than 12,000 (Braham 1984), while a second source estimates an initial population of 200,000 and a recent population of 75,000 (Gambell 1987). In any event, it is clear that sei whale numbers have incurred significant reductions. The numbers of humpback whales have dropped from over 120,000 worldwide to a current population of between 8000 and 10,000. Perhaps 2500 to 3000 remain in the southern hemisphere (World Wildlife Fund 1990; Johnson and Wolman 1984; U.S. State Department no date). Humpback whales feed both at and below the surface.

The right whale has declined in numbers from between 100,000 and 300,000 to only 3000–4000 worldwide; most of these reside in the southern hemisphere. It is known to penetrate into antarctic waters at least as far south as 65° S in the austral summer. Right whales usually feed ". . . by swimming slowly with their mouths wide open through the swarms of copepods" (Braham and Rice 1984). Sperm whales in the southern hemisphere initially may have numbered on the order of 1,200,000; as of the late 1970s, the southern stocks were believed to be composed of about 750,000 individuals (Gosho et al. 1984). Only male sperm whales migrate into antarctic waters, but these reportedly range as far south as the pack ice during the austral summer in search of their principal prey, medium and large-sized mesopelagic squid and, to a lesser extent, demersal (bottom dwelling) and mesopelagic fish (Gosho et al. 1984).

Most baleen whales spend about 120 days during the austral summer feeding in antarctic waters (Fifield 1987; Brown and Lockyer 1984). In their review of whale ecology in the Antarctic, Brown and Lockyer (1984) cite evidence by other researchers indicating that whales swim almost continuously and without slowing down during the night, at least during migration. Brown (1971) reported the recovery of a marked sei whale 3550 km from where it was marked in the antarctic only 10 days before. This individual thus averaged 14.5 km/h over the 10 day period. Sei whales may be able to sustain a speed of 18 or 19 km/h, blue and fin whales, a speed of 24 km/h. Humpback and right whales are considerably slower than the other large baleen whales.

REFERENCES

Braham, H. W. 1984. The Status of Endangered Whales: an Overview. In: *Marine Fisheries Review.* Vol. 46, No. 4: 2–6.

Braham, H. W., and D. W. Rice. 1984. The Right Whale, *Balaena glacialis*. In: *Marine Fisheries Review.* Vol. 46, No. 4: 38–44.

Brown, S. G. 1971. Whale Marking—Progress Report, 1970. *Report of the International Whaling Commission*, No. 21: 51–55.

Brown, S. G., and C. H. Lockyer. 1984. Whales. In: *Antarctic Ecology*, Vol. II, pp. 717–781. R. M. Laws, ed. Academic Press, New York.

Fifield, R. 1987. International Research in the Antarctic. Oxford University Press, Oxford.

Gambell, R. 1985. Antarctic Whales. In: *Key Environments—Antarctica*, pp. 223–241. W. N. Bonner and D. W. Walton, eds. Pergamon Press, New York.

Gambell, R. 1987. Whales in the Antarctic Ecosystem. In: *Environment International* . Vol. 13, No. 1: 47–54.

Gosho, M. E., D. W. Rice, and J. M. Breiwick. 1984. The Sperm Whale, *Physeter macrocephalus.* In: *Marine Fisheries Review.* Vol. 46, No. 4: 54–64.

Mizroch, S. A., D. W. Rice, and J. M. Breiwick. 1984a. The Blue Whale, *Balaenoptera musculus.* In: *Marine Fisheries Review.* Vol. 46, No. 4: 15–19.

Mizroch, S. A., D. W. Rice, and J. M. Breiwick. 1984b. The Fin Whale, *Balaenoptera physalus*. In: *Marine Fisheries Review.* Vol. 46, No. 4: 20–24.

Mizroch, S. A., D. W. Rice, and J. M. Breiwick. 1984c. The Sei Whale, *Balaenoptera borealis*. In: *Marine Fisheries Review.* Vol. 46, No. 4: 25–29.

Picken, G. B. 1985. Marine Habitats—Benthos. In: *Key Environments—Antarctica*, pp. 154–172. W. N. Bonner and D. W. Walton, eds. Pergamon Press, New York.

Sømme, L. 1985. Terrestrial Habitats—Invertebrates. In: *Key Environments—Antarctica*, pp. 106–117. W. N. Bonner and D. W. Walton, eds. Pergamon Press, New York.

U.S. Department of State no date. Final Environmental Impact Statement on the Negotiation of an International Regime for Antarctic Mineral Resources. Washington, D.C.

Walton, D. W. H. 1987. Antarctic Terrestrial Ecosystems. In: *Environment International* . Vol. 13, No. 1: 83–93.

World Wildlife Fund 1990. The Official World Wildlife Fund Guide to Endangered Species of North America. J. R. Matthews and C. J. Moseley, eds. Beacham Publishing, Inc., Washington D.C.

APPENDIX C

ESTIMATING THE PROBABILITY OF BALLOONS STRIKING ANTARCTIC BIRDS

Assume that each of 2.6×10^8 birds of all species in Antarctica (based on population estimates presented by Croxall 1987) presents a target area equivalent to a circle of radius $r_b = 0.15$ m (with an area of 0.071 m^2) to falling payloads of radius $r_p = 0.10$ m. Assume a random distribution of payload impacts in a 100 × 16,000-km zone along the entire coast of Antarctica, and that a total of 650 balloon payloads from McMurdo or 9000 payloads launched from all coastal antarctic stations in a year fall randomly within this zone. Under this scenario, the number of hits, H, on birds can be estimated as:

$$H = \pi(r_b + r_p)^2 \times N \times P \times T / A \qquad \textbf{(C.1)}$$

where:

$\pi(r_b + r_p)^2$ = effective target area of a bird of radius, r_b, = 0.15 m, that is subject to impact by a payload of radius r_p = 0.1 m

N = number of birds = 2.6×10^8 (The total effective target area of birds $[\pi(r_b + r_p)^2 \times N]$ = 51 km^2)

P = number of payloads falling per year

T = time in years

A = area of 100 × 16,000-km landing zone = 1.6×10^6 km^2

Thus, if 650 payloads per year from McMurdo fall into the 1.6×10^6-km^2 landing zone, the number of hits per year (out of the entire 2.6×10^8 birds of all species), H, would be only 0.021. In other words, an average of 48 years would pass before a single bird would be hit by a falling payload. If 9000 rawinsondes per year fall within the landing zone, about 0.29 birds would be hit per year, or one bird every 3–4 years.

REFERENCE

Croxall, J. P. 1987. The Status and Conservation of Antarctic Seals and Seabirds; a Review. In: *Environment International*, Vol. 13, No. 1: 55-70.

APPENDIX D

ESTIMATING THE PROBABILITY OF BALLOON-WHALE ENCOUNTERS

For a blue whale swimming/grazing through a finite area of water containing randomly distributed balloons considered as dimensionless points floating at the surface, the number of encounters over a given time may be calculated as the product of the area swept by the whale over time and the areal balloon density:

$$E = [W_g \times V \times T \times B]/A \quad \textbf{(D.1)}$$

where

E = number of encounters of whale with balloons,

W_g = whale's gape width (3 m),

V = average swim/graze velocity over time of interest (7.4 km/h),

T = time of interest (length of season in days),

B = number of balloons, and

A = area of finite water body.

The balloons, however, are not dimensionless, and, in fact, comprise several size classes as shown in Table 3. Moreover, we would like to be able to calculate the potential number of encounters for any number of whales over any number of seasons. Thus we include additional factors in Equation D.1:

$$E_{NS} = \sum_{i=1}^{n} [(W_g + L_i \cos \theta) \times B_i] \times V \times T \times N \times S/A \quad \textbf{(D.2)}$$

where W_g, V, T, and A are defined as above, and

L_i = deflated balloon length for i^{th} balloon size class,

$L_i \cos \theta$ = effective deflated balloon length for a whale approaching at a mean angle θ = 45°,

$W_g + L_i \cos \theta$ = effective width of whale's gape, given balloons have length $L_i \cos \theta$, and

N = number of whales,

S = number of seasons (years), and

B_i = number of balloons in i^{th} size class.

Although relatively few of the approximately 650 balloons released at McMurdo land in the sea or on sea ice (perhaps fewer than 20% of balloons launched from McMurdo), eventually most of the balloon and payload material should reach the sea via powerful katabatic winds and mass ice movement (generally in excess of 100 m/year in coastal areas, up to 2500 m/year in ice shelves; Fifield 1987). A plot of the landing locations of 12 balloons launched from McMurdo during August and September, 1992 (see Fig. 3, Table 2) shows that all came down between 98 and 215 km from McMurdo and within a sector defined by bearings 65° and 110°. All but two landed on the Ross Ice Shelf. The other two landed in the Ross Sea. The mean distance from the Ross Sea for all 12 balloons was estimated at 32 km. Currently available information is not adequate to permit estimation of how many years might elapse before balloons enter the sea at a rate comparable to the current launch rate, but if we assume that the current rate characterizes the past 10 or 20 years as well, then spent balloons may already be entering the Ross Sea at roughly the current launch rate. (The entry rate of 650 balloons/year is the average number of balloons that will be entering the ocean from the ice shelf when the number entering the ocean from the ice shelf equals the number landing on the ice shelf.) If balloon material is sufficiently strong and stable to last thousands to tens of thousands of years in the antarctic environment, then balloons launched from interior stations such as at the South Pole and Vostok will also eventually enter antarctic seas; however, balloons launched from these stations are not included in this analysis.

Assuming that downed balloon material remains essentially intact for a few decades, most balloons launched from McMurdo that do not directly enter the Ross Sea will probably be carried by ice movement to the sea. Other important assumptions in this analysis are

- that all McMurdo-launched balloons eventually enter and remain in a 100,000 km^2 region of the Ross Sea bounded by the ice shelf and a line paralleling the ice shelf at a distance of 100 km;
- that mean residence time for balloons in the region defined above is 2 years [based on probable maximum residence time in Ross Sea according to Ackley (S. F. Ackley, U.S. Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, personal communication to G.K. Eddlemon, ORNL, Oak Ridge, Tennessee, October 1993);

- that all balloons, including neoprene balloons (with attached styrofoam-encased instrument packages), float at the surface during their entire 2-year residence time in the Ross Sea;
- that the rate of balloon launches remains at 650/year indefinitely, balloon size class distribution remains as shown in Table 3 and the total length of all balloons afloat at any one time would be about 5.5 km;
- that marine mammals neither seek out nor avoid contact with balloon material;
- that adult blue whale gape width averages 3 m and velocity averages 7.4 km/h [4 knots—within the range of 2–7 knots suggested by Sears (R. Sears, Mingan Island Cetacean Studies, Mingan, Quebec, Canada, personal communication to G. K. Eddlemon, ORNL, Oak Ridge, Tennessee, October 29, 1993) and Goodyear 1993 (J. Goodyear, University of British Columbia, Vancouver, British Columbia, Canada, personal communications to G. K. Eddlemon, ORNL, Oak Ridge, Tennessee, October 27, 1993) as possible long term average velocities for the blue whale]; and
- that blue whales swim continually at the surface (residence time in the defined region is 120 days).

These assumptions are certainly not exactly correct (Sect. 3.2). They are pointed out here to show how refinements in knowledge about whale and balloon behavior can lead to refinement in interaction-rate estimates.

Factoring these assumptions into Equation D.2 above, the number of inadvertent encounters, E, by a single blue whale with floating balloons in the defined region of the Ross Sea over the course of one 120 day season would be approximately 1.7. If all neoprene balloons were assumed to sink immediately upon entering the sea, the encounter rate per whale would still be 0.44.

REFERENCE

Fifield, R. 1987. International Research on the Antarctic, Oxford University Press, Oxford.

APPENDIX E

MEMORANDUM TO USAP MASTER PERMIT FILE
1994-1995 BALLOON QUANTITIES

Ref. Permit—95 WM1—NSF A/ASA

MEMORANDUM

DATE: January 4, 1995

TO: USAP MASTER PERMIT FILE

FROM: Peter Karasik, Associate Compliance Manager

SUBJECT: 1994-1995 Balloon Quantities

On November 17, 1994 John Gress, ASA Science Support, provided NSF with updated information pertaining to planned balloon releases at McMurdo Station and at the Amundsen-Scott South Pole Station during the 1994-1995 austral summer season. Bob Cunningham and I reviewed the projected balloon release numbers relative to the number of balloon releases represented in the USAP Master Permit. Our conclusion was that the proposed balloon launches and materials are consistent with what is represented in the waste permit. In addition, 45 CFR 671.12(b) provides an exception which would allow the release of the balloons to the environment, since it would take extraordinary efforts and resources to recover these types of small balloons. The regulations state:

> ...wastes referred to in paragraph (a) [includes batteries, plastics, and other wastes which are constituents of balloons and ballon payloads] shall be removed from Antarctica to the maximum extent practicable [my underline].

The following table shows the waste permit estimates vs current projections for balloon releases at McMurdo Station. Updated numbers are in ()s.

Balloon Use	Payload Weight	Balloon		Number of Launches
		Size	Material	
Rawinsonde	220 g	650 m^3	Neoprene	596 **(560)**
Ozonesonde	220 g	200 m^3	Polyethylene	100
Ozone detector	620 g	500 m^3	Polyethylene	30
Ozone and particle detectors	4.8 kg	1,500 m^3	Polyethylene	12
Ozone and Condensation nuclei detectors	8.2 kg	4,000 m^3	Polyethylene	3
Long duration, high altitude	$\leq$2,000 kg	80,000 m^3	Polyethylene	2
Rawinsonde	220 g	200 m^3	Polyethylene	0 **(40)**

The following table shows the waste permit estimates vs current projections for balloon releases at Amundsen-Scott South Pole Station. Updated numbers are in ()s.

Balloon Use	Payload Weight	Balloon		Number of Launches
		Size	Material	
Rawinsonde	220 g	650 m^3	Neoprene	400 **(300)**
Rawinsonde	220 g	200 m^3	Polyethylene	100 **(200)**
Ozone detector	620 g	500 m^3	Polyethylene	80
Ozone and water vapor detectors	620 g	500 m^3	Polyethylene	6
Not available	Not available	80 ft^3	Not available	60
Microthermal Option A	1 kg	3 m^3	Rubber	0 **(30)**
Microthermal Option B	1 kg	538 m^3	Polyethylene	0 **(30)**

Note: Either Option A or Option B for microthermal balloons will likely be implemented, but not both A and B.

INTERNAL DISTRIBUTION

1-5. T. J. Blasing
6. G. E. Courville
7-11. G. K. Eddlemon
12. J. T. Ensminger
13. S. G. Hildebrand
14-18. L. N. McCold
19. C. I. Moser
20. J. G. Mural
21. H. D. Quarles
22. R. M. Reed
23. F. E. Sharples
24. R. B. Shelton
25. J. W. Webb
26. ORNL Patent Office
27. Central Research Library
28. Document Reference Section
29-30. Laboratory Records
31. Laboratory Records–RC

EXTERNAL DISTRIBUTION

32. Dr. Thomas E. Drabek, Professor, Department of Sociology, University of Denver, Denver, Colorado 80208-0209.
33. Dr. Stephen G. Hildebrand, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6037.
34. Mr. George F. Sowers, P.E., Senior Vice President, Law Companies Group, Inc., 114 Townpark Drive, Suite 250, Kennesaw, Georgia 30144-5599.
35. Dr. C. Michael Walton, Paul D. and Betty Robertson Meek Centennial Professor and Chairman, Department of Civil Engineering, College of Engineering, University of Texas at Austin, Cockrell Hall, Suite 4.2, Austin, Texas 78712.
36. ORNL Site Manager, U.S. Department of Energy, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6269.
37-38. OSTI, U.S. Department of Energy, P.O. Box 62, Oak Ridge, Tennessee 37831.