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Short Contribution

An Estimation of the Average Lifetime of the Latest Model of APEX Floats

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Estimating the average lifetime of floats is very important for Argo, because the total cost of maintaining the monitoring network largely depends on float lifetime. However, the actual lifetime of floats used in Argo is currently unknown. An estimate can be made by examining past float survival, but this is complicated by floats still operating at sea and continuous improvements in float hardware. Because APEX (Autonomous Profiling Explorer) floats are the most widely deployed type of float in the world oceans, in this study we estimate the lifetime of the latest model of APEX powered by alkaline batteries. The expected lifetime is estimated with a statistical method that allows for floats that are still active and that failed because of a known and now fixed hardware fault that should not cause failure in the latest model of floats. As an example, we analyzed the APEX fleets managed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), because we have access to a JAMSTEC database in which the causes of float failure have been carefully correlated to known hardware problems. Analysis of the JAMSTEC fleet (n = 571, as of 7 May 2008) indicated that the expected lifetime of the latest model of APEX is 134.6 (127.6–141.5, considering standard errors) cycles, equivalent to 3.7 years of 10-day cycles. We conclude that the annual deployment of 813 (773–859) APEX floats is needed to maintain the Argo observational network of 3000 floats. Floats with different hardware configurations (e.g., lithium batteries) or different mission programs (e.g., shallower profiling, deeper profiling every several cycles) may be expected to have an even longer lifetime.

Keywords:
· Argo project,
· profiling float,
· lifetime.

1. Introduction

The Argo Project, underway since 2000 (Argo Science Team, 2001), aims to maintain a network of 3000 Argo floats that provide real-time monitoring of temperature and salinity of the global upper ocean. In Japan, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), in cooperation with other agencies, is responsible for Argo (e.g., Iwasaka *et al.*, 2003).

Estimating the average duration of Argo float operation, or Argo float lifetime, is vital to the progress of Argo. This information is required in order to determine the annual number of floats that must be deployed to maintain the observation network. In other words, the total cost of the project is largely dependent on the lifetime of the floats; however, the average duration of float operation in the ocean has not previously been estimated. Normally, an Argo float is designed to have the battery capacity to measure about 150 conductivity-temperature-depth (CTD) profiles, which takes 4 years if 10-day cycles are assumed. This theoretical value is only achieved if all Argo floats continue their missions until their batteries are completely depleted. In reality, several factors other than "natural death" can cause floats to fail. In the case of JAMSTEC floats, more than half of the floats deployed at the beginning of the Japan-Argo project ceased operating within 2 years (shown later). Therefore, the factors influencing the survival of Argo floats at sea

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must be known so that their average lifetime can be estimated.

Several studies have previously been carried out on Argo float survival, based on float histories at sea (Roemmich *et al.*, 2004; Roemmich, 2005; Reste *et al.*, 2005; Argo Information Centre, 2005; Riser and Wijffels, 2005; Argo Steering Team, 2006), and some clearly showed that float survival had risen year-on-year owing to float hardware improvements. However, the methods used for these estimates were often not clearly defined, nor did they state the number of float measurements that could be expected over the floats' lifetime, especially for the floats currently in use.

One of the greatest difficulties in estimating float lifetime is that a large number of floats at sea are currently active; their actual lifetimes are therefore as yet unknown. Another is that the floats have been improved since Argo began and the most modern floats are very different from earlier ones. Thus, it is not meaningful to carry out a single analysis of old and new floats without considering their differences. It also means that survivability data for modern floats is available only for a short period. This situation is very similar to a difficulty commonly encountered in medical statistics, in which a statistical method known as survival analysis has been applied to bypass such issues. A similar method was used in the World Ocean Circulation Experiment (WOCE) to examine the average lifetime of a surface drifter and its extension thanks to hardware improvements (e.g., Sybrandy and Niiler, 1991; WOCE International Project Office, 1991).

The present study evaluated the lifetime of the latest model of APEX float using survival analysis of the JAMSTEC Argo fleet, as a careful study has already been undertaken to identify floats that ceased operating due to known causes.

2. Method and Data

2.1 Survival function and average lifetime

In order to estimate the expected period during which a float can operate, it is necessary to formulate a survival function $P(t)$ to quantify the proportion of floats still functioning at time t. When a survival function is generated, it is possible to calculate the average lifetime of a float, assuming that the survival function does not vary. This is simply written as follows:

$$\text{Average lifetime} = \int_0^\infty P(t)dt. \tag{1}$$

2.2 Estimation of survival function: The Kaplan-Meier method

In this study, a survival function is estimated by the Kaplan-Meier (KM) method (sometimes referred to as the product-limit method; Kaplan and Meier, 1958), which is commonly used in the field of medical statistics. The KM method gives the maximum likelihood estimator for the survival function.

The importance of this approach is that it provides a proper statistical framework for lifetime analysis with actual datasets which include: (i) individuals being still alive at the time of analysis; (ii) those with whom contact has been lost before their eventual death; (iii) those who have died of causes in which the study is interested; and (iv) those who have died of causes to be excluded from the analysis. The case of (iii) and (iv) is compared, for example, to a death from a cancer and one in a traffic accident in the study to determine the fraction of patients surviving for a certain period of time after cancer surgery: the classification between them depends on the purpose of the analysis. In the cases (i), (ii), and (iv), it is observed definitively that the individual has been alive for a certain period, but his/her actual lifetime is unknown in the analysis; such a case is referred to as a "loss" (also referred to in the literature as "censored"). Meanwhile, the lifetime is known in the case (iii), which is referred to as a "death" in this study. That is, individuals in the study either reach "death" or "loss".

For every float, the lifetime for analysis is defined as the number of completed cycles of profiling measurements (t_i) during the experiment. It is possible to formulate the statistics to allow for multiple "deaths" and "losses" occurring between discrete observation times. If the number of floats analyzed is n, then the set of times t_i is ordered so that $t_1 \le t_2 \le \cdots \le t_n$. Each lifetime corresponds to a single float, which either "died" or was "lost" during the experiment. Where lifetimes of multiple floats are identical, "deaths" are ordered before "losses".

For every t_i, the KM method estimates the probability of survival through the event at time t_i. If the i-th t_i was a "loss",

$$p_i = 1. \tag{2}$$

Thus, the "loss" of the float lifetime does not imply a reduced probability of survival for those that remain in the experiment. If the i-th t_i is a "death", then the number of floats in the experiment immediately prior to the death was $n - (i - 1)$, and the probability of survival is given by

$$p_i = \frac{n-i}{n-i+1}. \tag{3}$$

The KM estimator of the survival function P is given by

$$P_i = \prod_{j=1}^{i} p_j. \tag{4}$$

Table 1. Details of JAMSTEC Argo floats included in this study (as of 7 May 2008). Parking isopycnal means the float is designed to drift along a preset isopycnal surface shallower than 1000 dbar.

Parking	Profile	No. of deployed floats (in JFY)							
(dbar)	(dbar)	2000/01	2002	2003	2004	2005	2006	2007	Total
1000	2000			36	98	82(a)	76	79	371
2000	2000	18	36	43					97
isopycnal	2000		3	4	1(b)				8
1000	1500			12	16	10	10	11	59
1500	1500	4	28	2	1				35
isopycnal	1500						1(b)		1
Total		22	67	97	116	92	87	90	571

(a) Group includes 6 floats with oxygen sensors.

(b) Group includes one float with an oxygen sensor. JAMSTEC operates 13 other APEX floats with profile depths of 1000 dbar or shallower, which are removed from the analysis. Data are grouped by Japanese Fiscal Year (JFY, from April to March).

The KM estimator $P(t)$ is a step-like function of t and is reduced each time that corresponds to one or more "deaths". The formulation of the KM estimator also gives us the standard error E at time t_i corresponding to one of more "deaths" as follows:

$$E_i = P_i\sqrt{\sum_{j=1}^{i}\frac{1}{(n-j+1)(n-j)}}. \qquad (5)$$

2.3 *Float data*

We next analyze the database containing information about the 571 APEX floats managed by JAMSTEC (Table 1; complete as of 7 May 2008). This is one of the largest APEX fleets managed by a single operator. The floats are generally programmed to follow the Argo standard protocol (Argo Science Team, 2000), that is, to drift at a parking depth of 1000 dbar or deeper and always to profile to 2000 dbar; a buoyancy limitation of the hardware requires that 95 floats in the tropical regions only profile to 1500 dbar. None of the JAMSTEC APEX floats examined here had extra modifications, such as lithium batteries, to extend their operational lives.

The lifetime of a float in this study was defined as the number of successful profiles reported by a float before failure (death) rather than the number of the latest profile reported in the database, since some floats missed profile measurements due to unsuccessful surfacing or data transmission errors. In the JAMSTEC database, floats were considered to be dead when they perpetually stopped making normal profile measurements; this could include the following circumstances, under which a float can still report data:

- Pressure data become unreliable due to a pressure sensor failure (Argo Science Team, 2004). Once a float has such a symptom, its profiles become shortened, and finally it drifts on the sea surface.
- The float only updates the profile number or reports meaningless profiles because it is drifting on the surface continuously (Argo Science Team, 2002, 2003), runs ashore (Argo Project Office, 2005), is picked up contrary to the operator's intention, etc.

When floats were recovered deliberately by the operator (Shikama *et al.*, 2003; Oka and Ando, 2004; Oka, 2005), the float was considered to be "lost" for the purpose of the study, because this is very similar to the case (ii) described in Subsection 2.2. We believe that the above criteria are appropriate for the present study of float lifetimes and predicting the expected lifetimes of floats currently being deployed in Argo.

2.4 *Known causes of float death*

The APEX floats recorded in the JAMSTEC database include a number of floats that died prematurely due to hardware failures that were unrecognized at the time but have subsequently been identified. Hardware modifications have been made, so it is supposed that deaths resulting from these faults should not recur in APEX floats deployed recently and in the future. Thus, the latest model of APEX is expected to survive much longer than those deployed early in the Argo project (Fig. 1) and such deaths should be classified among the "losses" (case (iv) mentioned in Subsection 2.2) when the lifetime of the latest model is estimated. Table 2 summarizes the causes of death for 239 APEX floats in the JAMSTEC database, as determined by a careful study of engineering and sensor data at JAMSTEC. The objective of this paper is to estimate the survival function for the latest APEX. Each cause of death is explained below and then classified according to whether or not it could recur in the latest APEX.

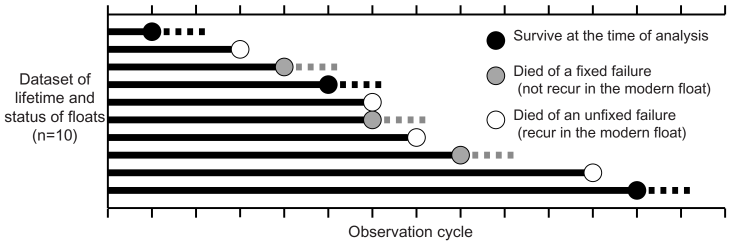

Fig. 1. Schematic of the treatment of float deaths used in estimating the survival function of the latest type of float using a dataset including older types of floats. If a float that died from a fixed failure were a new type of float, it would continue operating after the cycle at which its death is recorded (gray dashed lines). This situation is the same as that of an active float at the time of analysis (black dashed lines).

Table 2. Causes of death of APEX floats managed by JAMSTEC (as of 7 May 2008). Data are grouped by JFY.

Cause of death	Number of floats (in JFY)								Remediation
	2000/01	2002	2003	2004	2005	2006	2007	Total	
Pressure sensor failure		6	28	4				38	Fixed
Premature battery consumption									
Died before 73rd cycle	7	1	4					12	Fixed
Died during 74 to 114 cycle	3	4	20	13	2	1		43	—
Natural death[(a)]	3	37	28	18				86	—
Seasonal sea ice				7	6			13	Fixed[(b)]
Grounding	3		3					6	Fixed
Drifting ashore		2	1	1				4	—
Picked-up without intention		1	1					2	—
Unknown	2	9	9	8	1	3	3	35	—
Total of dead floats	18	60	94	51	9	4	3	239	
Recovered floats	4							4	
Floats operating at the sea		7	3	65	83	83	87	328	
Total of deployed floats	22	67	97	116	92	87	90	571	

(a)"Natural death" is the cessation of float operation after the 115th cycle due to battery drainage (voltage below 7 V).
(b)Assumes Argo fleet operates only in ice-free ocean.

2.4.1 Pressure sensor failure

One of the most common causes of death is pressure sensor failure (Argo Science Team, 2004), which caused 38 premature deaths, mainly in floats deployed in Japan Fiscal Year (JFY, from April to March) 2003, due to "snowflakes" in the sensor oil (e.g., Riser and Wijffels, 2005). This failure was addressed by early 2004, and manufacturing repairs were conducted twice (first, cleanup of the sensor oil, and second, improvement of the electronic board; N. Larson, personal communication, 2003, 2004; Table 3). At present the probability of occurrence is expected to be several percent (Riser and Wijffels, 2005) and it is also confirmed in the JAMSTEC database (Table 3).

2.4.2 Premature battery consumption

Premature consumption of float batteries is the other most common cause of APEX float death at JAMSTEC (55 cases, see Table 2). Here, premature consumption means death caused by battery consumption before the 115th cycle, most often accompanied by a sudden (problematic) drop in battery voltage. At JAMSTEC, a float death from battery consumption after the 115th cycle is classified as a "natural death" (Fig. 2, 86 cases in Table 2).

This category includes several failure modes which develop similar symptoms. First, this problem was identified as "energy flu" (e.g., Argo Science Team, 2002; Riser and Wijffels, 2005). Figure 2 shows the changes in

Table 3. Statistics of the pressure sensor failure occurrence (as of 7 May 2008). Remediation of this failure occurred in two ways: removing "snowflakes" in the pressure sensor oil (oil cleanup) and improving the electronic board to prevent appearance of them (N. Larson, personal communication, 2003, 2004).

Remediation	Total	Occurrence	Active floats	Cycles[a]
None	50	31	0	all died
Oil cleanup	33	3	5	124 to 125
Oil cleanup and electronic board improvement	402	4[b]	315	up to 155

[a] Measurement cycles of active floats at the time of analysis (7 May 2008).

[b] 4 floats with the most recent improved sensor (deployed in JFY2004) operated normally until the 25th, 68th, 85th, and 96th cycles.

battery voltage of APEX floats. Premature battery consumption failure was often found in floats fitted with an earlier type of controller board (APF6 or APF7), which were deployed in JFY 2000 and 2001 by JAMSTEC (see also Table 2). The problem was caused by short-circuits in these boards, which had defective solder mask layers that were hypersensitive to moisture, probably emitted by the alkaline batteries (Argo Science Team, 2003). Some floats with an improved board (the earlier type of APF8, deployed in JFY 2002 and 2003 at JAMSTEC) showed similar symptoms because of a defect in the battery pack cells (Shikama, 2005). Currently, both problems have been substantially solved (Argo Science Team, 2003; Riser and Wijffels, 2005) and there are no sudden battery voltage drops before the 75th cycle in the floats containing the later APF8 board (Fig. 2).

It is also noted that another type of APEX failure, motor backspin—in which high external pressures cause the float motor to spin backwards, in turn generating high current surges that damage float electronics (Argo Science Team, 2003, 2004)—sometimes causes a similar symptom to rapid battery voltage reduction. This problem has also been solved (Riser and Wijffels, 2005).

2.4.3 *Accidents in seasonal sea ice*

Thirteen APEX floats (deployed in JFY 2004 and 2005) have died from accidents in Southern Ocean seasonal sea ice, which prevents floats from reaching the sea surface and transmitting data. Some of the floats resume data transmission after the sea ice disappears; however, others die in the winter as they suffer damage from collision with the sea ice. Most of these deaths can be avoided by using an optional observation scheme (Ice Sensing Algorithm, Klatt *et al.*, 2007), and such deaths cannot occur in ice-free ocean areas, where the Argo floats are used mainly for the ocean observation network (Argo Science Team, 2001).

2.4.4 *Grounding*

Six APEX float deaths were attributed to grounding. If a float reaches the seabed while diving, sediment can become trapped inside the cowling that covers the buoyancy bladder, resulting in a loss of buoyancy (Shikama *et al.*, 2003). This can make it difficult for APEX to reach the surface at its next cycle due to its limited surplus buoyancy (D. Swift and S. Riser, personal communication, 2000; Izawa *et al.*, 2002). The current APEX float is programmed to dive again when it cannot reach the sea surface within a preset time, while repeated inflation and deflation of its bladder causes the sediment to move out of the cover. Modifications to the cover have also been made to reduce the likelihood of death from grounding. Therefore, the new APEX floats rarely die as a result of grounding, although some profiles may be missed.

2.4.5 *Others*

The other causes of float death—drifting ashore and being picked up contrary to the operator's intentions—are mainly attributable to a longer period drifting at the surface. The longer drifting period can be ascribed to low data transportation rates of the Argos communication system. It is therefore difficult to remedy this problem while the Argos system is in use.

It is also noted that several (35) float deaths whose causes have not yet been identified are classified as "unknown". Another failure mode may be found for these floats in the future.

2.5 *Float "deaths" regarded as "losses" in estimating lifetime of the latest APEX*

As described in the previous section, some of the causes of premature float death will not recur in current and future APEX floats. The framework of the KM method allows us to include these floats in the statistical analysis in order to estimate the survival function of the latest APEX by considering the float "deaths" as "losses", because a float that died from a fixed failure would continue to operate after the cycle of its death if it were the latest model of APEX, which is in the same statistical situation as a float operating at the time of analysis (see Fig. 1 and the case (iv) in Subsection 2.2).

Accordingly, deaths from pressure sensor failures (except for 4 deaths of floats with the most improved sen-

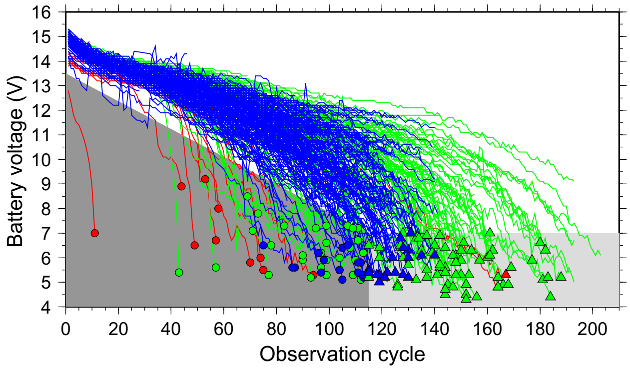

Fig. 2. Changes in float battery voltage of APEX floats used in this study (as of 7 May 2008). Circles and triangles represent float deaths from premature battery consumption and natural causes. Red represents floats equipped with either the APF6 or APF7 electronic board. Green and blue represent those with earlier and later types of APF8 board, respectively. Darker and lighter shaded areas represent JAMSTEC definitions of death from premature battery consumption and natural death, respectively.

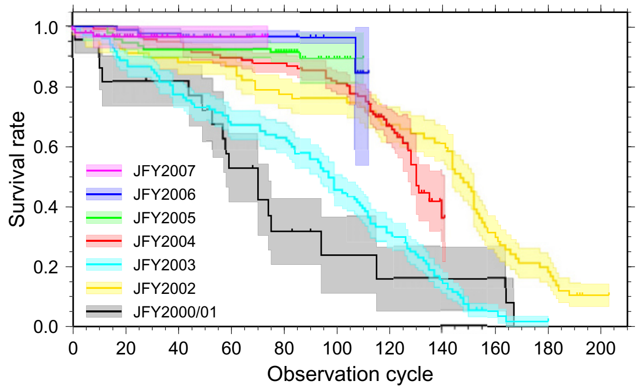

Fig. 3. Survival functions of JAMSTEC APEX fleets deployed in each Japanese Fiscal Year (as of 7 May 2008) obtained by applying the KM estimator to the records (i.e., making no adjustment for float deaths from failures that had already been fixed). Shaded areas represent the standard errors of the functions estimated by Eq. (5). Short sticks on the functions represent the cycles of floats regarded as "losses".

sor, see Table 3), premature battery consumption before the 73rd cycle, and grounding are considered to be "lost" in the KM framework. Deaths from accidents in sea ice are also regarded as "losses" to estimate the lifetime of floats operating in the ice-free ocean. Deaths due to drifting ashore, premature pickup by someone other than the operator, and all other unknown causes remain classified as "deaths". The threshold of the 73rd cycle (2 years of 10-day cycles) for premature battery consumption is based

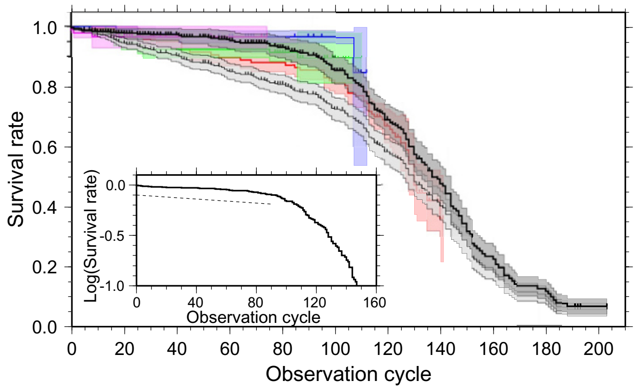

Fig. 4. Survival function (with standard errors) estimated for the latest APEX as of 7 May 2008, which is free from failures that have already been fixed (solid line with darker shading). The thin line (with lighter shading) represents the KM estimator (with standard errors) applied to the record of the JAMSTEC APEX fleet considering all recorded float deaths as "deaths". Colored lines represent the survival functions of APEX deployed in JFY 2004 (red), JFY 2005 (green), JFY 2006 (blue) and JFY 2007 (magenta), as in Fig. 3. Short sticks on the functions represent cycles of floats regarded as "losses". Inset panel shows a logarithmic plot of the survival function of the latest APEX. The slope of the dashed line corresponds to a death rate of 0.10% per cycle.

on the manufacturing report (D. Webb, personal communication, 2006). This seems reasonable (and somewhat moderate) for the latest APEX because no floats with the most recent controller board died before the 75th cycle from this cause, and only a few died before the 100th cycle (see Fig. 2).

3. Results

3.1 Improvement of float survival

First, we show survival functions of JAMSTEC APEX fleets sorted by year deployed (Fig. 3), which are simple applications of the KM estimator to the float datasets, i.e., considering all recorded float deaths as "deaths" (hereafter called KM estimators for the recorded data). The survival rate of the JAMSTEC APEX fleet has improved gradually, as described for another fleet in previous studies (e.g., Roemmich *et al.*, 2004; Argo Information Centre, 2005; Riser and Wijffels, 2005), although survival rate varied widely in Argo's early stages. More than half of the APEX floats deployed in JFY 2000 and 2001 died within 2 years, mainly from energy flu (see Subsection 2.4.2). Addressing this issue dramatically enhanced the survival rate of the APEX fleet in JFY 2002 (e.g., Riser and Wijffels, 2005; see also Table 2). The fleet's longevity may also be attributed to the higher ra-

Table 4. Summary of the lifetimes of JAMSTEC APEX floats evaluated in this study (n = 571, as of 7 May 2008). Unit is observation cycle. Average: average lifetime calculated using Eq. (1). Median: number of cycles completed when the survival function becomes less than 0.5 (the expected cycle when just half of deployed floats survive). Values in parentheses are estimates considering the standard errors as the upper and lower boundary.

Average	Median	Note
120.6 (114.5–126.7)	130 (126–135)	Apply KM estimator to the JAMSTEC APEX fleet record*
134.6 (127.6–141.5)	137 (133–142)	Estimation for the latest version of APEX

*KM estimator is simply applied to the record of all APEX floats in the JAMSTEC database, i.e., considering the recorded float deaths as "deaths".

Table 5. Effect of premature death on float lifetime estimate. Estimates of float lifetime considering constant death rates (0.05%–0.3% per cycle) during a float's entire life, under the assumption that all floats finally die at a fixed cycle determined by battery capacity (theoretical lifetime). The values in parentheses express estimated rates in the theoretical lifetime. Cycles 146, 182, 219, 255 and 292 correspond to 4, 5, 6, 7 and 8 years, respectively, using a 10-day measuring cycle.

Death rate	Theoretical float lifetime									
(per cycle)	146		182		219		255		292	
0.05%	140.8	(96.4%)	173.9	(95.5%)	207.4	(94.7%)	239.3	(93.8%)	271.6	(93.0%)
0.1%	135.8	(93.0%)	166.3	(91.4%)	196.6	(89.8%)	225.0	(88.2%)	253.1	(86.7%)
0.2%	126.5	(86.6%)	152.4	(83.7%)	177.1	(80.9%)	199.5	(78.2%)	220.9	(75.7%)
0.3%	118.0	(80.8%)	140.0	(76.9%)	160.2	(73.2%)	177.9	(69.8%)	194.1	(66.5%)

tio of the floats with shallower-profile measurements (see Table 1). The APEX fleet in JFY 2003 was, unfortunately, severely damaged by pressure sensor failure. After JFY 2004, the JAMSTEC fleet expanded to the Southern Ocean; in the first 2 years, some floats did not survive the first winter due to unexpected seasonal sea ice. The survival of the most recent APEX fleets (JFY 2006 and 2007) is fairly good, even though we can calculate it only for short periods and with larger error in the latter part of the survival function. It is noted that the improvements of float survival rate since JFY 2004 seem steady, but all survival functions are within their estimation errors.

3.2 *Survival function and expected lifetime of the latest APEX*

Figure 4 shows the expected survival function for the latest model of APEX, which is calculated using "deaths" and "losses" as defined in Subsection 2.5. The expected survival rate of the latest APEX decreases very slightly during cycles 0–90, and the average death rate at each cycle is estimated to be 0.10%. The survival function then drops gradually in cycles 90–140. About 85% of the deployed floats are expected to continue operating beyond the 100th cycle, and half will survive until the 137th cycle (133–142 cycles, considering the standard error). Additionally, this result shows that about 20% of the floats will complete more than 160 profiling measurements.

Figure 4 also shows the survival rates of APEX fleets deployed after JFY 2004, the same ones as in Fig. 3, for comparison. The survival of the recently deployed APEX fleets is very consistent with the estimate for the latest APEX within the standard error, which supports the applicability of the present statistical approach and the appropriateness of the assumptions concerning the failure modes for the latest APEX. It also suggests that the estimated survival function is useful for predicting the future survival rate of recently deployed APEX floats. Of course, it is possible that hidden hardware changes in recently deployed floats could have introduced some failure mode which will appear later in their lives and which is not represented in the earlier floats. In that case, the survival rate would be below the curve in Fig. 4.

It is now possible to calculate from Eq. (1) the expected number of profiles that a new (latest version) APEX float should report. Therefore, we expect the lifetime for the latest APEX, or for those yet to be deployed, to be 134.6 cycles (3.7 years of 10-day cycles, Table 4), or 127.6 to 141.5 cycles, considering its standard error. Here, we assume that the survival rate decreases linearly from the end of the estimation (0.0676 at the 203rd cycle) to 0 at the 210th cycle to enclose the function, which changes the integration by less than 1 cycle. This result depends to some degree, of course, on the float configurations of the JAMSTEC APEX fleet.

4. Discussion

This study has introduced the KM method, which is widely used for statistical analysis in the medical sciences, to estimate the expected lifetime of APEX floats managed by JAMSTEC. This specific subset of the Argo fleet was selected because a careful study has already been undertaken to identify floats that had ceased operation from known causes. The methodology reported here could be applied to an analysis (for example, conducted by other national operators) of any other subset of the global Argo fleet in which float failure has been identified.

The expected number of cycles that the latest APEX will perform is estimated as 134.6 (127.6–141.5, considering the standard errors). Thus, recently deployed APEX floats are expected to operate at sea for 3.7 (3.5–3.9) years on 10-day-cycles in the case of the APEX configuration used at JAMSTEC. Furthermore, 813 (773–859) floats should be deployed every year to maintain the Argo network. Floats with different hardware configurations (e.g., lithium batteries) or different mission programs (e.g., shallower profiling, deeper profiling every several cycles) may be expected to have even longer lifetimes, which may reduce the number of annual deployments.

This study has also estimated the death rate of modern APEX floats at 0.10% per cycle until the 90th cycle (about 2.5 years of 10-day cycles). This rate is much better than an estimate by Roemmich *et al.* (2004), in which the death rate for the Argo floats of the United States (including many APEX floats) deployed in 2003 was 0.2–0.3% in the first year after deployment. The main reasons for the difference are that float hardware has been continuously improved and our estimate for the latest APEX was made 3 years later than theirs.

Concerning the death rate, it should be noted that APEX floats rarely die from initial failures. Generally, the death rate of a manufactured product is higher at the beginning of its operation than in the middle of its lifetime. The low initial death rate of APEX probably shows that the float has been mechanically refined. Moreover, part of it may be related to few failures during float deployment by JAMSTEC, which results from the technical experts' preparatory inspections at the laboratory and close cooperation with ship crews.

This estimate of 3.7 years (134.6 cycles) is very close to the theoretical lifetime of APEX, which is 4 years or 150 cycles. Considering that many of the latest APEX floats will die long before their theoretical lifespan (i.e., about 15% floats will die before the 100th cycle), the average lifetime of the float at sea will differ more from the laboratory estimate when the theoretical lifetime is extended by future improvements (Table 5), even though the death rate of the float is very low. Since the theoretical lifetime takes almost no account of float survival before battery consumption, the floats with longer potential lifetimes will be exposed to other accidents at sea for much longer periods.

5. Summary

Estimating the expected lifetime of floats is one of the most important issues for the Argo project, because the total cost of maintaining the monitoring network largely depends on float lifetime. We have provided a statistical framework, the Kaplan-Meier estimator, which enables the accurate assessment of floats still operating at sea and floats that died from hardware faults from known causes which have been already fixed and will never recur in floats being deployed now or in the future. We applied this method to the JAMSTEC APEX fleet, because a careful study has already been undertaken to identify the causes of float deaths. By carefully treating floats that failed due to issues that have been corrected, the KM estimator can now be applied to a combined dataset of floats from all development years and all float generations' hardware to estimate a single survival function.

The lifetime of all APEX floats used by JAMSTEC, including all past failures, is expected to be 120.6 cycles (114.5–126.7 cycles, considering the standard error) for 571 floats (see Table 4) after applying the KM estimator to the record. When failures that have been already fixed are regarded as "losses" rather than "deaths", we can estimate the survival function and expected lifetime of a newer (latest type) APEX float that is free of known hardware faults. Such a survival function is presented in Fig. 4 and is consistent with the actual survival function of recently deployed floats.

The number of cycles that the latest APEX is expected to be able to accomplish is 134.6 (127.6–141.5, including the standard error). Thus, recently deployed APEX floats are expected to operate at sea for 3.7 (3.5–3.9) years, making 10-day cycles in the JAMSTEC float configurations. This also means that 813 (773–859) floats need to be deployed annually to maintain the Argo observation network of 3000 floats. Floats with greater battery capacity or energy saving schemes are expected to have even longer lifetimes.

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Observing System. The data from Argo profiling floats are freely available.

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