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Autonomous Pinniped Environmental Samplers: Using Instrumented Animals as Oceanographic Data Collectors

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Abstract

Data recording tags applied to marine animals store data for later retrieval and can return valuable information on animal behavior and ecology including habitat preference, physiology, and movement patterns, as well as environmental data. If properly instrumented, calibrated and archived, data from these tags can add to the oceanographic data stream for parts of the ocean where data are sparse or lacking. In this study we examine such data from northern elephant seals instrumented with time-temperature-depth recorders (TTDR) and ARGOS platform terminal transmitters. Northern elephant seals range widely over the northeastern Pacific on long foraging trips. The seals dive continuously on these trips to depths of 400 to 600 m.

Between March 1998 and March 1999, 6 female and 3 male elephant seals were tagged in central California and data were collected during subsequent foraging trips. Temperature and depth were measured and stored every 30 sec and retrieved after the animals returned to the rookery months later. Portions of the track where both ARGOS and TTDR data were available from these 9 animals averaged 4634 km over 67 days with 2.4 ARGOS positions per day. Mean dive duration was 20 min and mean dive depth was 428 m. A comparison of temperature profiles from seal TTDR with GTSPP subsurface data showed very good agreement, as did surface temperatures to other sources of SST. We describe quality control of the data and entry into the World Ocean Database (WOD). A total of 75,665 autonomous pinniped bathythermograph (APBT) profiles over the 41,702 km of seal trackline were added to the WOD.

Biological autonomous sampling systems have immense potential to contribute oceanographic data in a cost-effective manner. The northern elephant seal represents but one species covering portions of the northeast Pacific Ocean. Research programs presently exist on a variety of species, including southern elephant seals and other pinnipeds, tunas and billfish, sharks, seabirds, marine turtles, and whales. With improving technology, such tags will be applied to even more marine animals and the approach described here can be applied to other species to improve ocean data availability.

1. Introduction

The ability to conduct research on the behavior and movements of oceanic animals has been markedly improved by miniaturization of electronic components and sensors. Electronic tags have been used in an expanding range of biological applications. Passive integrated transponder tags, for example, provide identification of individual animals but relatively little else (Brannas et al. 1994). Telemetering tags, using either acoustic or radio frequency communication, transmit data in real time and can be used to track or monitor animals directly or with remote recording stations (Brill et al. 1995). Archival tags, which may have various sensors, record and store data for later retrieval after the animal is recaptured. These small electronic tags, with their continually improving measurement accuracy, can return valuable information including habitat preferences, physiological data, environmental data, and movement patterns, and their use has been expanding to a wide variety of animals (Boehlert 1997).

If properly instrumented, calibrated and archived, selected information from such tags has great potential to add to the oceanographic data stream for parts of the ocean where data are sparse or lacking (Costa 1993; McCafferty et al. 1999; Campana et al. 2000; Koudil et al. 2000). Still, two issues have hindered the widespread use of such "biological autonomous" collection of oceanographic data. First, unless data are telemetered by satellite, the animal must be recaptured in order to make use of the data contained in the tag. Adequate recapture rates require deployment either in large numbers (with concomitant expense) or on animals with high likelihood of return. Return rates have been relatively high for animals with homing behavior and low mortality rates, such as marine mammals (Le Boeuf et al. 2000; McCafferty et al. 1999; Lagerquist et al. 2000) or sea turtles (Polovina et al. 2000). Fishes have moderately high mortality rates. To date, the greatest successes have been with high value species, such as salmon (Walker et al. 2000) or bluefin tuna (Block et al. 1998). In this case, high recapture probabilities in fisheries result in moderately high return rates.

The second problem is determination of the position where data were collected; for many tags, geographic position is poor or lacking. Tags able to record geoposition are generally too large except for large and robust animals. Data recording tags placed on many fish, for example, have had no mechanism to determine position with the exception of tagging and recovery locations (Walker et al. 2000). Archival tags with light sensors that estimate longitude from time of sunrise or sunset and latitude from day length have been applied to several species (Wilson et al. 1998; Tuck et al. 1999). Locations derived from these tags have relatively large theoretical variances. Under practical application, where animals may reside at different depths and weather systems may impact measured light intensity, the error may be even greater (Welch and Eveson 1999). A more recent development which partially addresses both return rate and location information is the "pop-up" tag, programmed to release from the animal after a pre-set time and then to transmit its data to a satellite (Block et al. 1998). While the data volume transmitted by these tags is limited to a recent series of temperature-depth profiles, the technology is improving; moreover the tags can be programmed to continue transmitting SST data for 30 days (Lutcavage et al. 1999).

Larger animals, with a lower mortality rate and higher likelihood of return, are able to carry a larger instrument package. Elephant seals (Mirounga angustirostris), for example, offer a unique system to carry instrumentation and to collect environmental information with high value from an oceanographic standpoint (Costa 1993; Le Boeuf et al. 2000). From California rookeries, this species ranges widely over the northeastern Pacific on foraging trips that last from 2 to 9 months. Migration patterns differ between the sexes; females may migrate throughout the northeastern Pacific, while males migrate to destinations along the continental margin from coastal Oregon north to the Aleutian Islands. Females are at sea on average 3 months during the spring migration and 7 months during the summer-fall migration. Adult females increase their body mass during both migrations, the second of which includes gestation. Northern elephant seals dive continuously, exhibiting extremely long duration dives (mean = 22 min., max =120 min.) with short surface

intervals (1-3 min). Dives are routinely to 600 m, with dives as deep as 1600 m. Unlike other diving pinnipeds, elephant seals do not dive in bouts; extended periods at the surface are extremely rare (Le Boeuf et al. 1986; Costa 1993; Le Boeuf et al. 2000).

Animals from the above studies are instrumented with time-temperature-depth recorders and ARGOS platform terminal transmitters. Although large volumes of environmental information have been collected during the tagging studies on these animals, the principal purpose has been to evaluate the behavior of the seals rather than ocean conditions (Costa 1993). Thus, the objectives of this paper are to evaluate existing temperature profiles taken from instruments attached to northern elephant seals from throughout the central and eastern North Pacific, to add these records to the NOAA World Ocean Database (WOD, Levitus et al. 1998), and to provide an example for other biological researchers to collect data in formats and approaches consistent with submission to common physical databases.

2. Methods

a. Tagging

All elephant seal tagging occurred at the Año Nuevo rookery in Central California (37.11º N, 122.33º W). Data on diving behavior, ranging and migration, and distribution of elephant seals by time of year, sex, and age, have been collected since 1990. Tagging techniques and decisions on timing of tagging (to assure temporal proximity to departure date) were based on past experience. Tagging procedures, animal handling, and tag recovery procedures are fully described in Le Boeuf et al. (2000) and will not be repeated in detail here. It should be noted, however, that the procedures are conducted under research permits from the U.S. National Marine Fisheries Service and are also reviewed by an Institutional Animal Research Care and Use Committee. They are not deemed to be harmful to these animals.

b. Instrumentation and Data Handling

1) ARGOS Transmitters

Half-watt satellite platform transmitter terminals (PTT, Model ST-6, Telonics, Mesa, Arizona) were affixed near the animal's head using epoxy (Figure 1); the epoxy is shed during molting after the animal returns from its migration. The antenna was oriented to be out of the water when the seal surfaced. The PTT transmitted every 34 sec while the animals were at the surface. Because of the small antenna, the relatively low power of the transmitter, and the limited surface time, each surface period will not provide a position fix. Consequently, positions were determined using the ARGOS system with Auxiliary Location Processing (ALP), wherein lower quality locations (class A & B) are still calculated and reported (Taillade 1992). Estimates of mean errors were also based on animals hauled out at Año Nuevo. The rookery is basically a 1 km bight and the location in the center of the bight, determined by GPS, was used as a comparison with the ARGOS position.

Locations were further filtered using standard methods used by marine mammal tracking studies (see McConnell et al. 1992). This method starts with the time the animal enters the water at Año Nuevo and iteratively compares the distance to each succeeding ARGOS position. The resulting transit rates are compared to a reasonable maximum transit speed for the elephant seals. For this project we used a conservative 3.0 m/s transit speed. Each subsequent hit is either accepted or rejected. When the filter rejects a location (LOC(x)), its location quality and IQ (an inverse index of residual frequency error and frequency drift; i.e. high IQ equals a high confidence in signal characteristics) are compared to the preceding location (LOC(x-1)). If the rejected location (LOC(x)) was of higher quality or same quality but higher IQ than the preceding hit (LOC(x-1)), the alternative of rejecting the previous hit was considered. If rejecting the previously accepted location (LOC(x-1) results in reasonable transit speeds from the previous hit (LOC(x-2)) to the current higher quality location, LOC(x) was accepted and LOC (x-1) was rejected. This process was continued until the end of the location data for each animal.

We also performed empirical tests to determine the uncertainties introduced into the

position estimates caused by variable times between fixes. This is difficult, however, because seals are actively moving in different directions with time. Thus, deviations from a straight trackline are compounded by the directional behavior exhibited by the animal. We analyzed the ARGOS track data by sequentially dropping out intermediate fix positions, estimating the location of the intermediate point by linear interpolation, and then taking the difference (in km) from the actual ARGOS position. Given three ARGOS position fixes $P_{(i)}$, $P_{(i+1)}$, $P_{(i+2)}$, a straight line was drawn from $P_{(i)}$ to $P_{(i+2)}$; based upon the elapsed time to the intermediate position, $P_{(i+1)est}$ was calculated and the distance between $P_{(i+1)}$ and $P_{(i+1)est}$ is an estimate of the deviation from the track. This was done iteratively for all tracks in the study and the results related to time and distance between ARGOS positions.

2) Time-Temperature Depth Recorders (TTDR)

Temperature and depth were measured with Mk 3 data recording tags (Wildlife Computers, Seattle, Washington). This instrument has a temperature resolution of 0.1 ˚C and accuracy of 0.5 ˚C. All of the TTDR had a manufacturer's stated minimum recording temperature of 4.8ºC, although one instrument showed truncation of data records at 5ºC. This TTDR was carried by 2 animals in the dataset. Minimal temperatures recorded were examined for each animal; if evidence of truncation was noted, records at and below this temperature were discarded. Because the thermistor was contained in the housing on this model, temperature response was delayed; the factory-estimated time constant was 1 min. Water bath experiments performed on units prior to deployment suggested that thermal characteristics of the housings on all tags used were close to identical. To evaluate the time constant for correcting temperature from the field, an instrument was set to record at 5 second intervals (those deployed on animals were set to record each 30 sec) and lowered on a wire along with a SeaBird conductivity-temperature-depth (CTD) recorder. The lowering and retrieval speed were similar to that of seal dives. The two data records (Mk 3 and CTD) were

aligned and differenced at each measurement from the Mk 3. This was done with successive 5 sec time offsets (no offset, 5 sec, 10 sec, 15 sec.....,60 sec). The time constant chosen for application to the field was that with the lowest sum of absolute values of the differenced data.

Temperature calibration curves were determined for each TTDR using a water bath and a thermistor (.01ºC)/datalogger. The resultant linear regressions were used to correct raw temperature data. Slopes ranged from 0.97 to 1.01; intercepts ranged from -0.21 to 0.31. Two TTDR's yielded nonlinear calibration curves and data from those animals were not included in the dataset. The pressure transducers on the TTDRs were calibrated prior to deployment using a pressure station. All Mk3 TTDRs used have two transducer channels. In order to increase accuracy on shallower dives TTDRs were programmed to use channel 1 for depths <450m (with accuracy <2m) and channel 2 for depths >450m (with accuracy <4 m).

In the field, TTDRs were attached to the animals' pelage on the dorsal midline above the shoulders using epoxy (Figure 1). TTDR data were recorded in memory every 30 sec and retrieved after the animals returned to the rookery months later. A potential problem noted by McCafferty et al. (1999) that was solar insolation on the tags (as the seals remained at the surface) raised the recorded temperature above the ambient SST. Elephant seals dive continuously, however, with surface intervals typically less than three minutes; during that time, only the head breaks the surface, with the TTDR remaining submerged (Le Boeuf and Crocker 1996). Thus, effects of solar insolation on recorded temperature were not deemed to be a problem.

3) Data handling

Upon return from the field, data files were modified using a program from the manufacturer (Wildlife Computer, Zoc.exe Vers. 1.27) to correct zero offset in depth. This program allows visual inspection of all dives and correction for surface drift. Since the animal returns to the surface after each dive, offset is set accordingly for each dive. Some records do not require an offset correction, some records have a constant offset correction for the entire file, some records drift and require

several offset corrections. Data were also offset by 30 sec to accommodate the time lag described above. Two data files for each animal were available, one with time-temperature-depth and another with time and location from the ARGOS fixes. In most animals, there were periods where either or both TTDR or ARGOS data were lacking, and these periods were excluded from further consideration in this study. Data from the two files were aligned; the seal temperature data have roughly 2880 points per day, whereas only 2-3 ARGOS locations are available per day. After temporally aligning each ARGOS position to its respective TTDR data points, all other TTDR points were assigned a geographic position location through linear interpolation between adjacent ARGOS locations.

The Ocean Climate Laboratory/National Oceanographic Data Center (OCL/NODC) World Ocean Database (WOD) stores data as individual oceanographic profiles. Each profile has a single position and date (e.g., latitude, longitude, month, day, year, time), and contains depth-dependent variables (e.g., temperature, salinity) sorted from the shallowest to the deepest depth. The seal time series data were processed into the WOD data format. Each seal's depth-temperature times series was divided into "dives". A dive was defined as a data series starting at the surface (depth = 0 m) which increases in depth to maximum depth (the bottom of the dive), and then returns to the surface (the end of the dive). Each dive was then split into two profiles: a down cast (all points from the start of the dive to the bottom of the dive), and an upcast (all points from the bottom of the dive to the end of the dive). The cast direction (up/down) was stored, and then the profile was sorted (from shallowest to deepest depth). During the sorting process, repeated depth measurements (periods of horizontal hovering, typically at the surface or bottom of a dive) were removed. The profiles were then run through standard WOD quality control checks (range checks; density, gradient, and inversions checks; annual, seasonal, and monthly standard deviation checks against the WOD98 temperature climatologies; see Conkright et al. 1998).

For simplicity, the date and calculated position of the first measurement within each upcast or downcast were used for the date and position of that profile. The difference in time since the

previous ARGOS fix and until the next ARGOS fix were then calculated and stored. If that profile was the closest profile to an ARGOS fix, it was also assigned an ARGOS quality flag (containing a code for the ARGOS signal quality).

3. Results

The database of northern elephant seal tracks with ARGOS and TTDR data for this study includes 6 females tagged between March 1998 and March 1999 and 3 males tagged in March 1997 (Table 1). Collectively, these animals were tracked for a total of 858 days. Animals traveled an average total distance of 6944 km over average duration 95 days, with mean dive depths of 428 m on average each 20.3 min. Males typically make shorter duration trips than females, but several of the female trips in these data were during El Niño years and were shorter than normal, apparently due to some effects of an altered foraging environment. Transit speeds of males were greater than that of females. Because much of their foraging is on the continental shelf region, mean dive depths of males is less than females. More detailed information on behavior and differences between the sexes is provided in Le Boeuf et al. (2000).

Failure of either the TTDR or ARGOS PTT during these tracks resulted in a reduction of the total number of useful days for the current study to 605 days tracked, a loss of 29% of the total days at sea (Table 1). Nonetheless, given a 30 sec sampling interval, this still represents some 1.74 million temperature depth pairs with locations. The tracks of the animals in this study (Figure 2) demonstrate the long-distance movements by northern elephant seals. Females, tracked in 1998-9 show a wide range of patterns, with some animals foraging on the continental slope and others in the open North Pacific. Males tracked in 1997, on the other hand, tend to rapidly move northwest along the coast and spend time foraging at different places along the continental slope (Figure 2, top). Incomplete tracks for the males associated with loss of data from either instrument are seen clearly in the male data. The track for Moose is complete from start to finish, whereas tracks for the other two males have only data for the outgoing leg of the track.

The shape of the time-depth curves differ as a function of activity. Le Boeuf et al. (2000) described four types of dives. The three most frequently observed are V-shaped dives (Figure 3A), which occur mainly during transit, dives with distinct bottom times with multiple vertical excursions that characterize pelagic foraging (Figure 3B), and dives with flat bottoms, characteristic of animals transiting or foraging along the continental shelf/slope (Figure 3C). The frequency of dive type differs between male and female seals and also differs between sexes when animals are in transit or on their focal foraging areas (Le Boeuf et al. 2000). These profiles demonstrate the regularity of the dives and the short surface interval between dives. An approximation of the mean speed of descent or ascent can be calculated based upon mean depths and dive durations (Table 1). Estimates are 0.83 m/sec for females and 0.49 m/sec for males. The lower value for males is likely related to the shallower dives and the higher frequency of flat-bottom dives.

a. Calibration of Temperature and Depth

A comparison of temperatures recorded from a CTD and a Mk 3 demonstrates the lag characteristic of this instrument (Figure 4). With a 5 sec sampling interval on the Mk 3, the individual measurement points are clearly evident. Lagging the Mk 3 data by 30 sec resulted in a much closer correspondence with the CTD temperatures. A range of lag times from 0-60 sec were compared by taking the absolute value of the deviations from each point measured with the Mk 3 to an equivalent temperature at that depth from the CTD. The mean deviations (Figure 5) were minimal (0.18 ºC) at a 30 sec lag, differing from the manufacturer's estimated time constant of 1 min. For data collected from the field, a 30 sec lag, representing a shift of one point, was made as a correction to all data.

b. Location Accuracy

The number of ARGOS locations per day ranged from 1.2 to 4.3, with an average of 2.5 positions per day (Table 1); filtering these data resulted in a loss of 5.8% of the of the positions.

Mean errors were calculated based on animals hauled out at Año Nuevo. The rookery is a 1 km bight and the location in the center of the bight was used as a comparison (GPS position ± 0.5 km depending where the animal was located). Location accuracy for these animals hauled out on the beach, based upon relatively static locations (Table 2) suggests a wide range of mean errors. For comparison, the distribution of ARGOS quality markers for the tracks used in this study is shown in Figure 6 along with the data from Table 2. The distribution of fixes when the animals are at sea are skewed towards the poorest quality positions compared to when the animals are stationary on land. This is obviously related to a combination of factors, including the duration of surface activity, the antenna being partially submerged during rough seas, and the relatively low power output of the transmitter.

The error associated with ARGOS is compounded by the time (and distance) between ARGOS position fixes during which temperature and depth data continue to be collected. It is further compounded by the behavior of the elephant seals. Because the seals exhibit turning and movement behavior while at sea, linear interpolations between fixes may introduce errors. The empirical tests of iteratively dropping out alternating ARGOS fix positions and then estimating that position based on linear interpolation between the two adjacent positions showed differences between males and females. The average of this deviation was 16.3 km for the three males and 8.04 km for the six females. The difference between sexes is probably related to the longer time interval between fixes for males and females -- females in this study had ARGOS fixes on average 2.3 times as frequently as males (Table 1). This probably represents a difference in behavior at the surface affecting reception and therefore PTT performance. For both males and females, the deviation was linearly related to the time between adjacent fixes; the slopes of the significant regression lines are 7.26 km/day for females and 6.53 km/day for males. In general, however, the averages are consistent with, and probably not distinguishable from, the errors inherent in the ARGOS locations (Table 2).

c. Comparisons with existing temperature data for the North Pacific

The regularity and depth of dives by these instrumented animals provide an excellent source of surface and subsurface temperature data (Figure 7) that is not unlike that from towed profiling systems (Aiken et al. 1999). Temperatures recorded by TTDR on northern elephant seals were compared with other sources of temperature data from the North Pacific region. First, the magnitude of data collected by the northern elephant seals is emphasized in the numbers of observations for the time period March-May, 1998. GTSPP subsurface data (see http://www.nodc.noaa.gov/GTSPP/gtspp-home.html) for this three month period show relatively sparse observations; in the area bounded by 36°N to the south, 58°N to the north, 150°W to the west, and the west coast of North America to the east, there were 166 GTSPP observations that measured to at least 10 m. During the same period, five female seals made 22,131 dives distributed throughout the region (see Figure 2). Even combining adjacent dives to generate profiles or subsetting the data in some other way (such as with location quality flags), the available data quantity is substantial.

Given the magnitude of additional subsurface data, concern exists for potentially introducing a false "climate signal" caused by changes in instrumentation. This kind of signal has been observed in the COADS database, for example, in changes from Beaufort Scale to anemometer measurements for wind, changes from bucket SST to using engine intake measurements on vessels, or where meteorological buoys are added to a given location (Folland and Parker 1990; Roy and Mendelssohn 1998). To examine potential bias or signals introduced in measurements from elephant seals, we compared surface and subsurface temperature measurements from seals with those collected by traditional means. SST data derived from seals (zero depth temperatures only) were compared with surface Reynolds temperatures (Reynolds and Smith 1994; see http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/) over a range of temperatures (Figure 8). These results show a strong and positive correspondence between these two sources of SST data.

Subsurface data from seals were similarly compared with GTSPP subsurface data (see http://www.nodc.noaa.gov/GTSPP/gtspp-home.html). We took a statistical approach to this analysis, comparing profile data in 1-degree square, 1 month bins in February through May, 1998. Within these time-area strata, all coincident data from seals and GTSPP profiles were compared by differencing average values at 5 meter depth intervals between the surface and 500 m. After removing flagged profile data from the GTSPP series, there were a total of 12 one-degree/month strata with both seal and XBT data. The XBT data typically consisted of one or two profiles being compared with a large amount of APBT data. Differences ranged between -0.91 to 1.30 ºC, with average 0.02 and standard deviation 0.39. Although data were variable, there appeared to be patterns; from the surface to 90 m XBT values tended to be warmer, whereas below 300 m XBT values tended to be cooler. We also compared Reynolds surface temperatures for these same locations and times. Mean surface temperatures were 10.28 ºC, 10.50 ºC, and 10.95 ºC for APBT, Reynolds, and XBTs, respectively. This is consistent with the comparison with the Reynolds surface data with corresponding APBT data (Figure 8).

It is useful to compare the cost-effectiveness of the temperature profiles obtained in this study with more traditional profiles such as XBTs. Even ignoring the costs for vessel time, temperature profiles from northern elephant seals come at low cost. Personnel costs for tagging and recovery are approximately 16 hrs per deployment on northern elephant seals. This includes programming, packaging, deployment, and recovery of the tags. In addition, approximately 4 hrs per deployment are spent in data handling. Given the nine animals in this study and the number of profiles, the personnel costs are trivial -- 0.02 min per APBT or 0.88 min per APBT with corresponding ARGOS fix. This is certainly less than the cost of handling associated with XBT casts. The financial costs are also relatively low. For the animals used in this study, the ARGOS PTT cost $2250, the TTDR cost $2000, and each ARGOS fix cost $5.40. This translates to a cost for the nine animals in this study of $0.67 per APBT or $34.31 per APBT with corresponding ARGOS fix. All of these values have been discounted for the average 92% recovery rate for

northern elephant seals (LeBoeuf et al. 2000) and for instrument failure, but do not take into account the fact that the instruments can be re-used after recovery. Compared to current costs for an XBT, the APBTs are highly cost-effective.

d. Seal Data in the WOD

A total of 75,665 profiles (coded as APBT, for autonomous pinniped bathythermographs) were defined as described above and stored in the WOD (Figure 10). The data were minimally processed to preserve as much of the original data resolution as possible. Ancillary information (e.g., information on the temperature sensor, the ARGOS signal quality, and the time offset from the previous and next ARGOS fix) were stored to allow the WOD user to process and tailor the data to a resolution that fits their needs. As an example, a user could select only upcast profiles, or those taken within one hour of an ARGOS fix; 1478 profiles had an associated ARGOS fix (Figure 10). The average vertical distance between adjacent data points in these profiles is 30.0 m for females and 20.1 m for males. These data will be available in the next release, WOD-2001.

One quality control check included comparisons of the seal TTDR temperatures with the WOD98 annual, seasonal, and monthly climatologies. This essentially checks the temperature values against the WOD98 analyzed mean value of the entire 1x1 degree grid. If the difference is >3 standard deviations from the WOD98 analyzed mean, that observations is deemed a "statistical outlier". If a profile has more than two statistical outliers in it, the entire profile is flagged. Although this is not a fool proof check (i.e., legitimate features can be flagged), it does provide a quick review of the data. Analyses on all the seals showed varying percentages of flagged profiles (Table 3). The seals STORM and RAIN are particularly noteworthy, with over 20% of their profiles flagged. Unlike many of the other females, however, both spent more time near the coast (Figure 2), where the one-degree WOD98 climatologies may be less than optimal. Moreover, the seal PETE was in the same general area a year earlier, and has a very low percentage of flagged profiles. As an El Niño year, 1998 was unusually warm (Lynn et al. 1998) and January through

April coastal temperatures were far higher than normal (Schwing and Moore 2000). Because over 99% of the flagged profiles were at higher (rather than lower) temperature values than the climatological boundaries, these profiles are likely valid.

4. Summary and Conclusions

This is the first study clearly demonstrating that biological autonomous sampling systems, such as northern elephant seals, have the potential to provide oceanographic sampling that is on par, in terms of quality, with other contemporary sampling systems. Using data from migrations from only nine animals over three years, we have added nearly 76,000 temperature-depth profiles in the northeast Pacific (Figure 10) to the World Ocean Database (Levitus et al. 1998).

The northern elephant seal example shown here represents but one species covering portions of the northeast Pacific Ocean (Figure 2). Existing tag technologies are allowing new research to understand the distribution, behavior, and ecology of marine animals. Research programs presently exist on a variety of species, including southern elephant seals (Boyd and Arnbom 1991), tunas and billfish (Block et al. 1997), sharks (Sims and Quayle 1998), seabirds (Hunt et al. 1990; Wilson et al. 1998; Tuck et al. 1999; Koudil et al. 2000), and whales (Craig and Herman 2000; Lagerquist et al. 2000). It is likely that such tags will be applied to more marine organisms. As an example, a major scientific undertaking called the "Census of Marine Life" (CoML; Ausubel 1999; see also www.coml.org) views electronic tags as an important new technology (Stone et al. 1999), Two current CoML pilot projects, called "Pacific Ocean Salmon Tracking" and "Tagging of Pacific Pelagics" are focused on use of electronic tags. With continued miniaturization, improvements in sensor technology, and geolocation techniques (Welch and Eveson 1999), more of these data will become appropriate for use in oceanographic studies.

Implementation of expanding ocean observation systems will require greater availability of oceanographic data from varied sources. Already, vessel of opportunity programs (Emery et al. 1997), profiling floats (Roemmich and Owens 2000), and autonomous underwater vehicles

(Bellingham et al. 2000) are improving ocean data. The procedures we have outlined in this study may serve as a model for data recorded from tagged animals when it meets the requisite criteria for data quality and geolocation. This innovative approach, however, can serve as an important adjunct to other means of collecting oceanographic data to meet community goals of improving ocean data availability.

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Figure Legends

Figure 1. Adult female elephant seal with ARGOS satellite transmitter and Mk 7 TTDR attached. Observations of behavior at sea suggest that only the head is out of the water, so the location of the TTDR on the back means that it is submerged during surface behavior and thus temperature measurements reflect ocean temperature.

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Figure 7. Dive profiles (line) and thermal structure from a time-temperature-depth recorder on a

northern elephant seal from a series of dives over a period of 9.6 hours on March 16, 1998. The seal was located at 42.58° N lat., 144.63° W long. Note the regularity of the dives.

Figure 8. Comparison of seal-derived SST data with weekly Reynolds surface temperatures. Data are derived by taking the mean surface temperature from the TTDR values within a single week-1 degree square stratum and comparing it with the weekly mean Reynolds value for the same time and location. Data points were taken from throughout the region the animals moved (Figure 2) and represent nine seals from 1998 (for the week ending 3 March) and five seals from 1997 (for the week ending 1 April).

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Table 1. Data from northern elephant seals used in the current study. All animals began their tracks in March of the year indicated. Total days tracked represents the entire time the animals migrated, between departure from the rookery and return. WOD days tracked represents only those days where both ARGOS and temperature-depth records were available. The following four columns represent data from only those days, whereas the last two columns are averages from the entire duration of the TTDR recording.

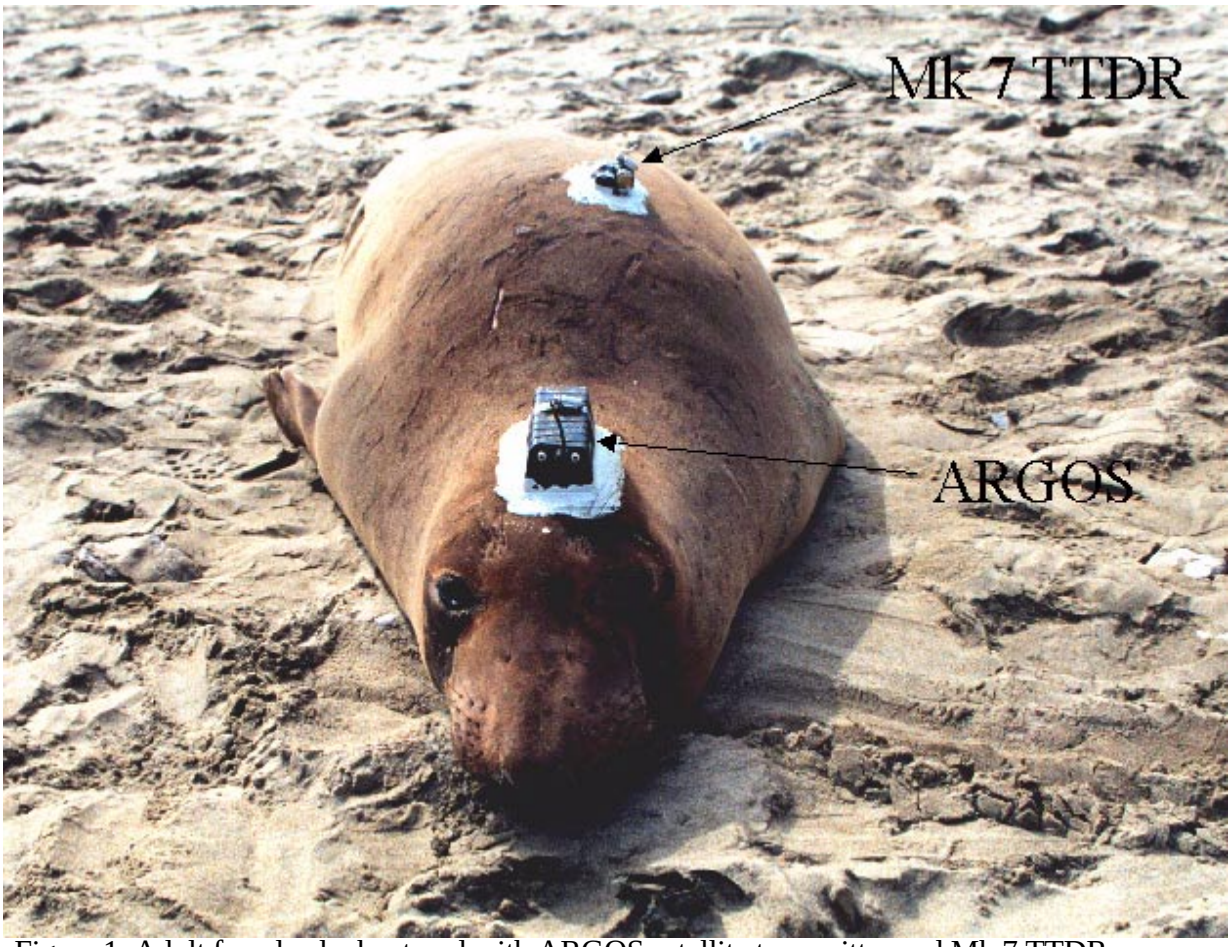
Seal	Sex	Start date	Total Days Tracked	WOD Days Tracked	ARGOS Fixes	Fixes per day	Transit (km/d)	Distance (km)	Mean Dive depth (m)	Mean dive duration (min)
Wave	F	1998	98	79.73	229	2.872	64.64	5153.8	459	18.4
Storm	F	1998	64	18.63	39	2.093	53.34	994.0	462	22.2
Rain	F	1998	94	73.32	197	2.687	58.26	4271.6	494	21.8
Sun	F	1998	87	63.31	237	3.743	84.98	5379.9	520	18.3
Gale	F	1998	94	92.20	229	2.484	63.77	5879.3	549	19.4
Sun2	F	1999	88	88.51	383	4.327	75.11	6647.5	434	18.4
Moose	M	1997	114	112.27	147	1.309	69.14	7762.1	279	23.2
Pete	M	1997	120	16.33	24	1.470	109.62	1790.3	366	20.8
Bopp	M	1997	99	60.70	72	1.186	62.99	3823.7	291	19.9
Means										
Female			87.5	69.28	219	3.03	66.68	4721.01	486.33	19.75
Male			111.0	63.10	81	1.32	80.58	4458.70	312.00	21.30
Overall			95.3	67.22	173	2.46	71.32	4633.57	428.22	20.27
Total			858	605.01	1557			41702		

Table 2. Data on the ARGOS satellite fix and location accuracy based upon static trials with animals in the rookery (from Le Boeuf et al. 2000). The actual comparison was subject to an error of +/-0.5 km because the GPS position for comparison was based at the center of the rookery and the animals often move to different parts of the rookery.

Location Quality	Stated Accuracy (ARGOS)	Number	Error Mean (km)	Standard Deviation (km)	Range (km)
3	< 150 m	338	0.8	0.1	0.3 -1.8
2	150 - 350 m	302	1.4	0.6	0.6 - 3.4
1	350-1000m	403	2.7	2.1	0.5 - 14.9
0	> 1000m	323	9.3	15.5	0.6 - 78.4
A	None given	164	28.3	50.7	0.5 - 123.1
B	None given	78	48.4	70.4	0.7 - 237.6

Table 3. APBT profiles added to the WOD from the current project. The flags, described in the text, are the percentages of total profiles flagged in the quality control process due to individual temperature records exceeding certain differences from the annual, seasonal, or monthly climatology in WOD98.

Seal	**Year**	**Total Profiles**	**Annual flags**	**Seasonal flags**	**Monthly flags**
PETE	1997	1865	0.10%	0.10%	0.10%
MOOSE	1997	10612	0.20%	1.00%	0.50%
BOPP	1997	7397	1.20%	4.20%	7.50%
RAIN	1998	8379	23.40%	20.60%	20.60%
STORM	1998	2043	32.00%	28.00%	30.10%
WAVE	1998	10681	18.20%	18.30%	18.50%
SUN	1998	11620	7.40%	15.50%	15.80%
GALE	1998	11904	2.40%	1.60%	1.60%
SUN2	1998	11164	1.70%	3.00%	4.50%



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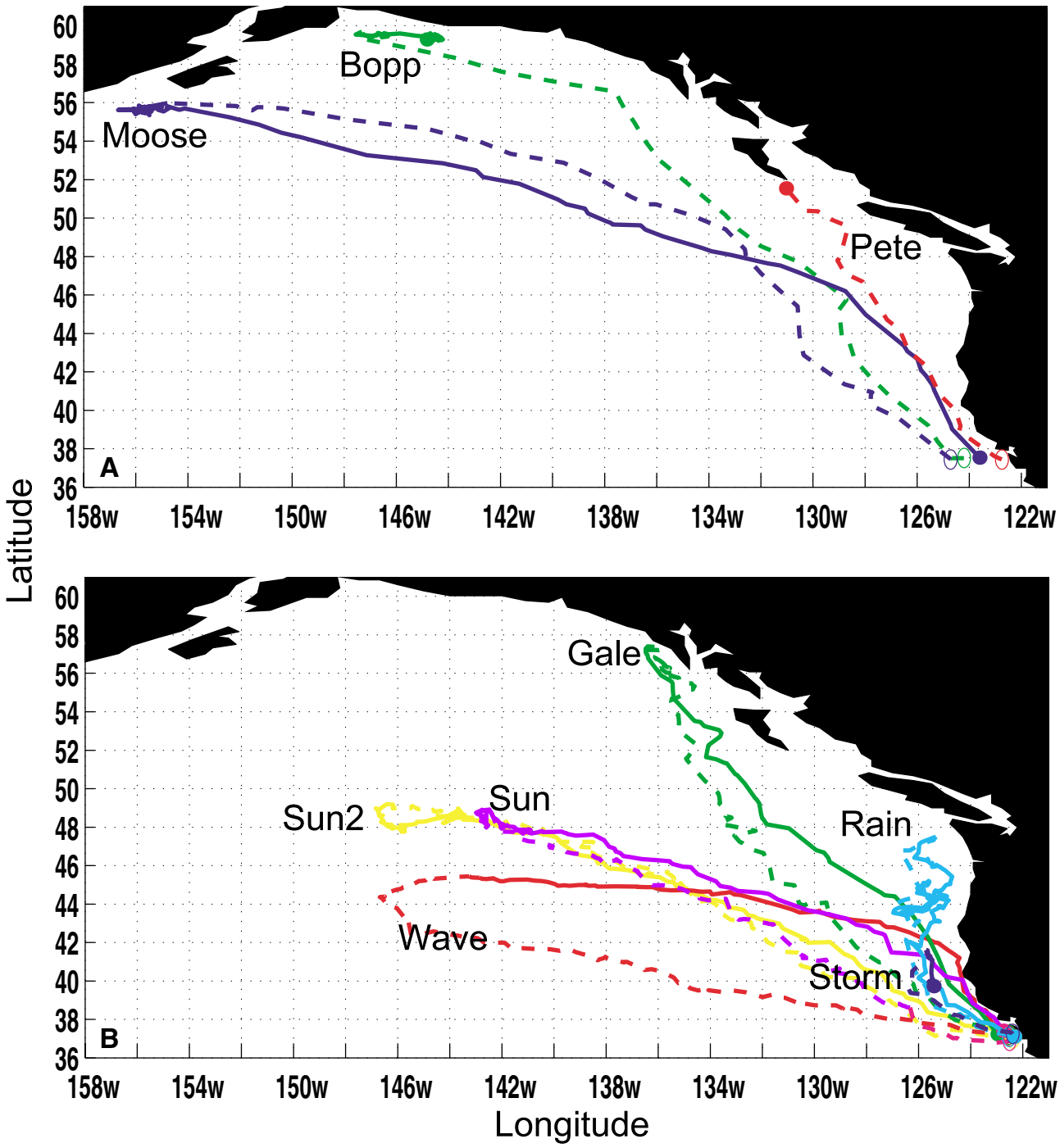

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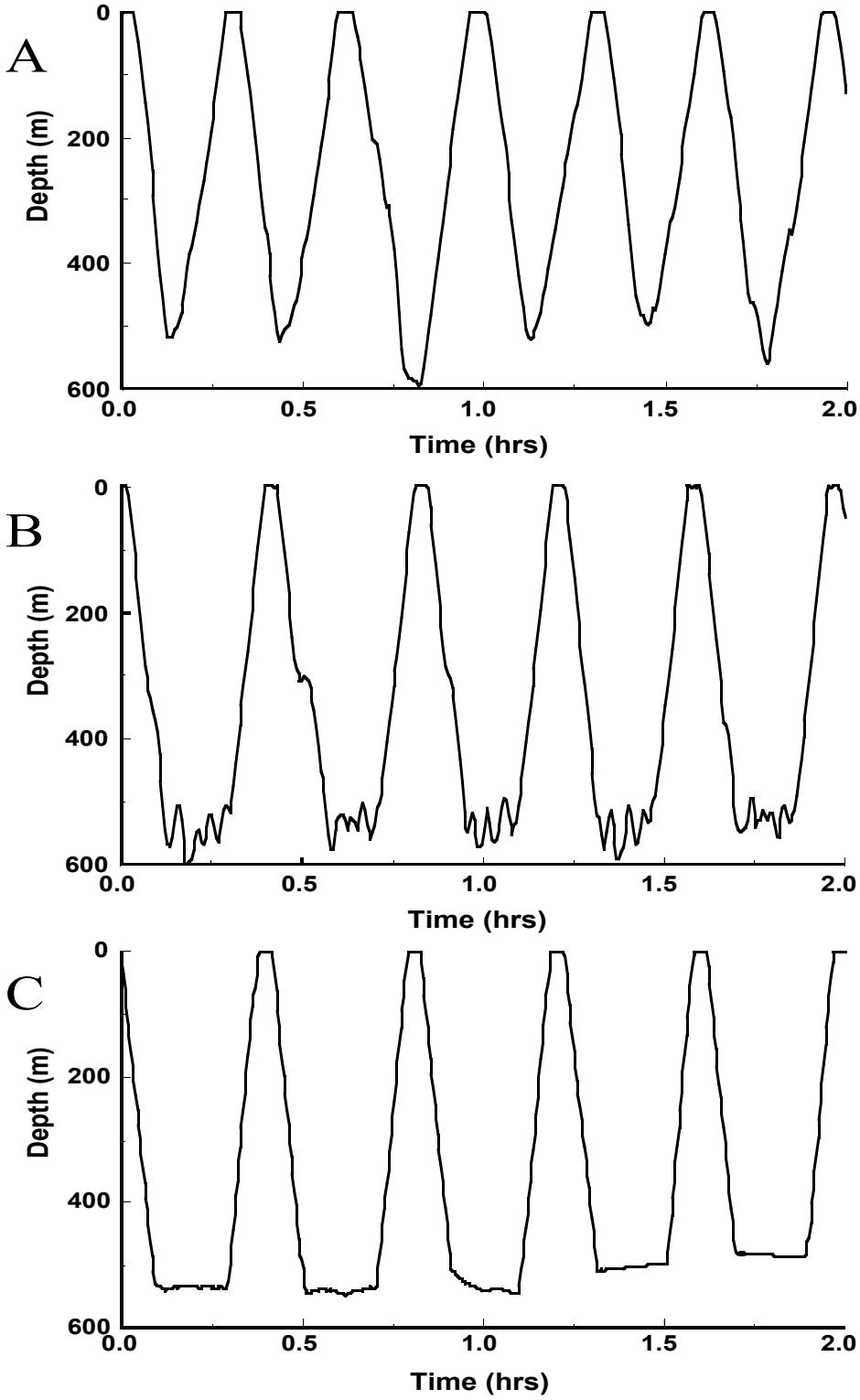

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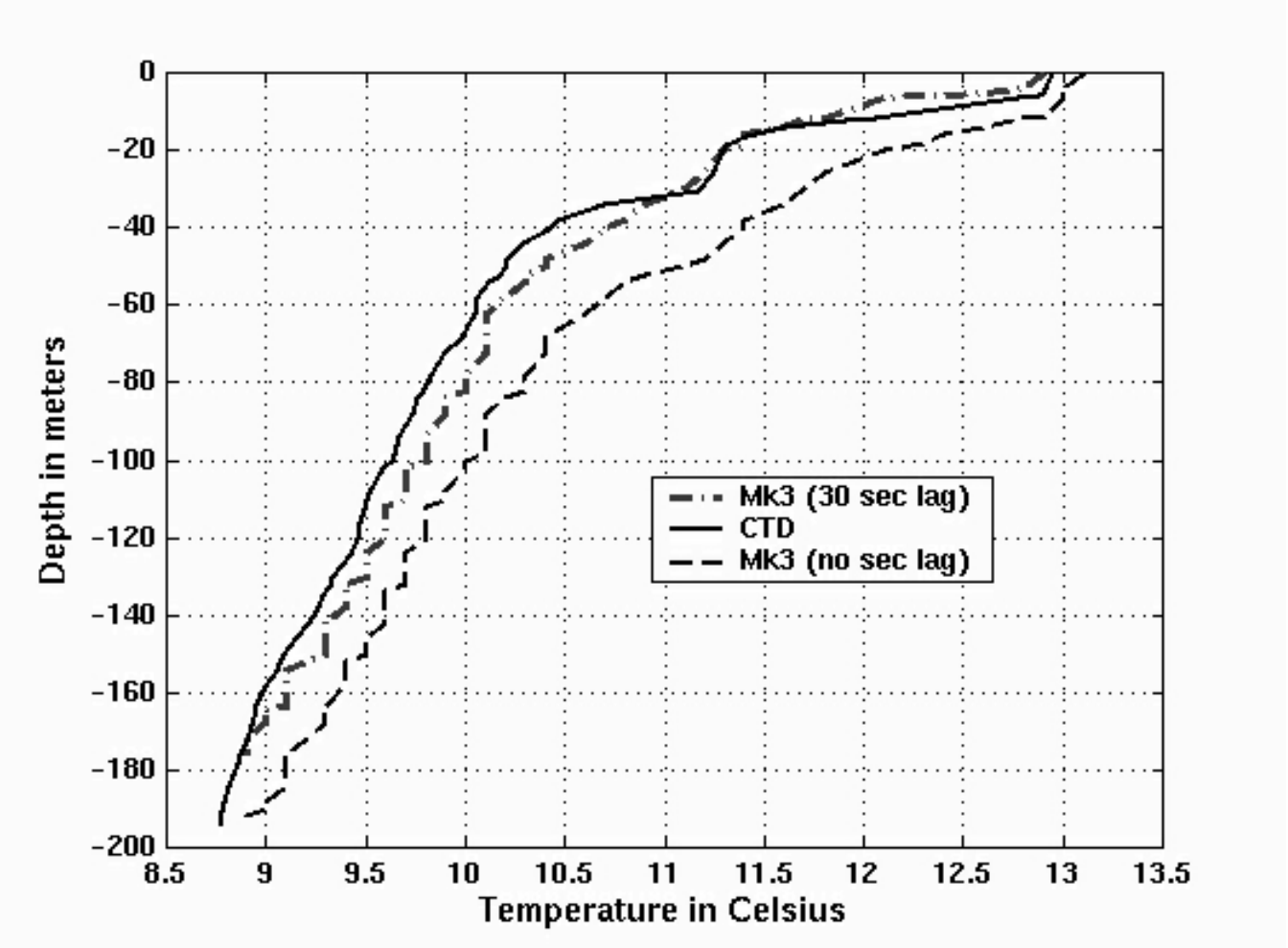

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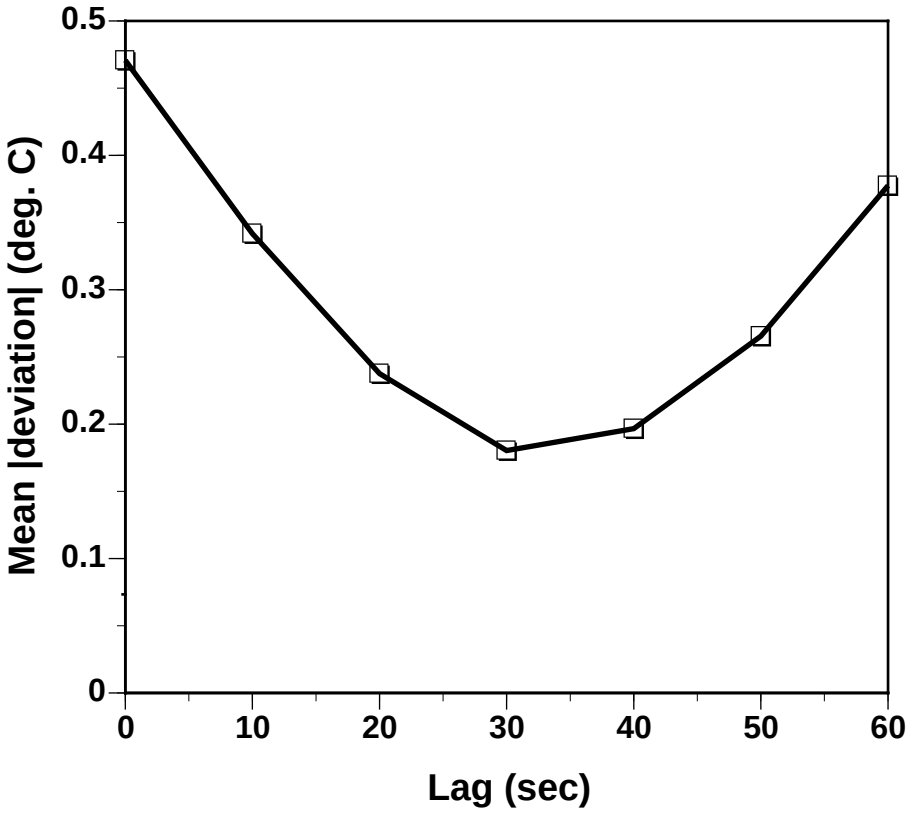

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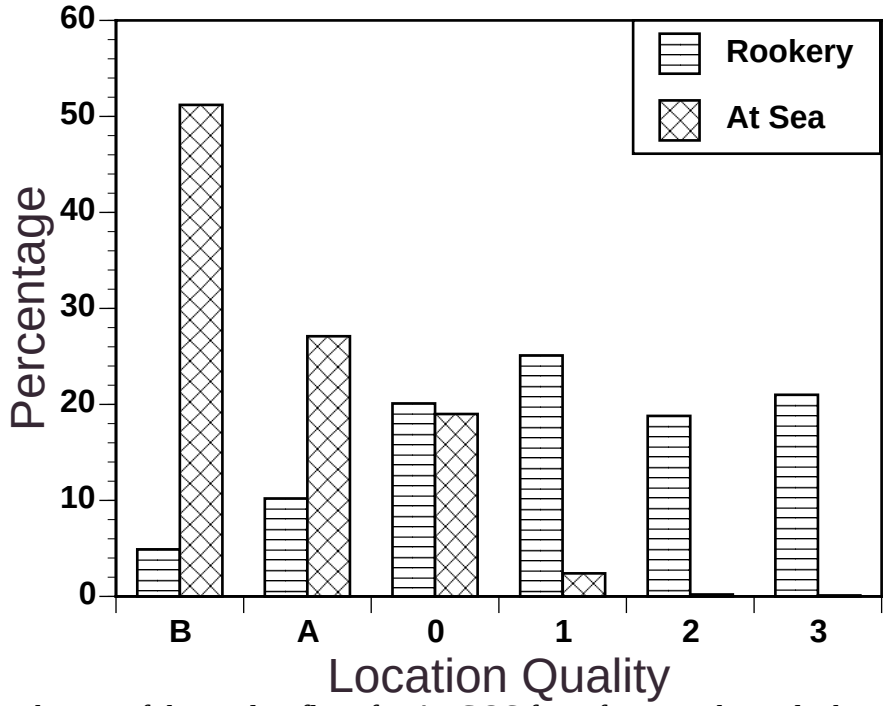

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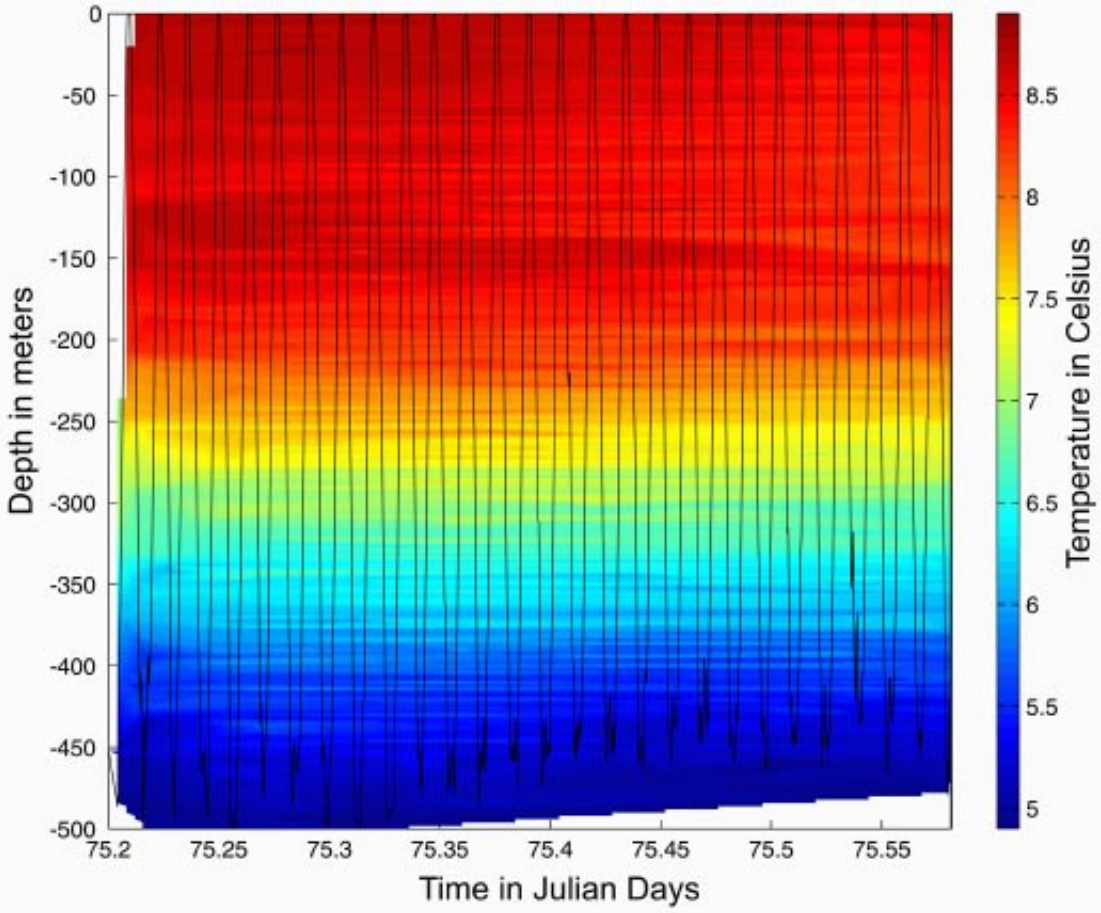

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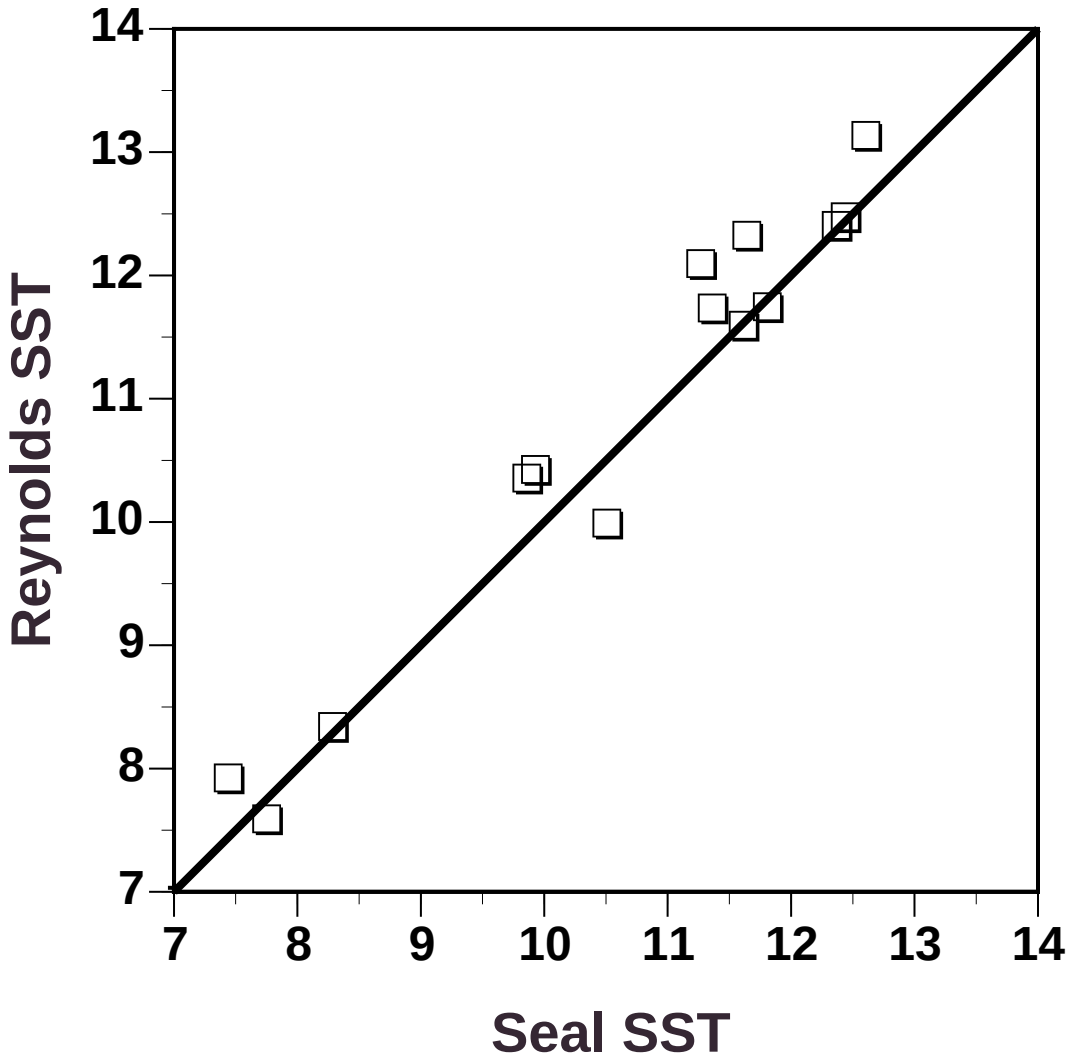

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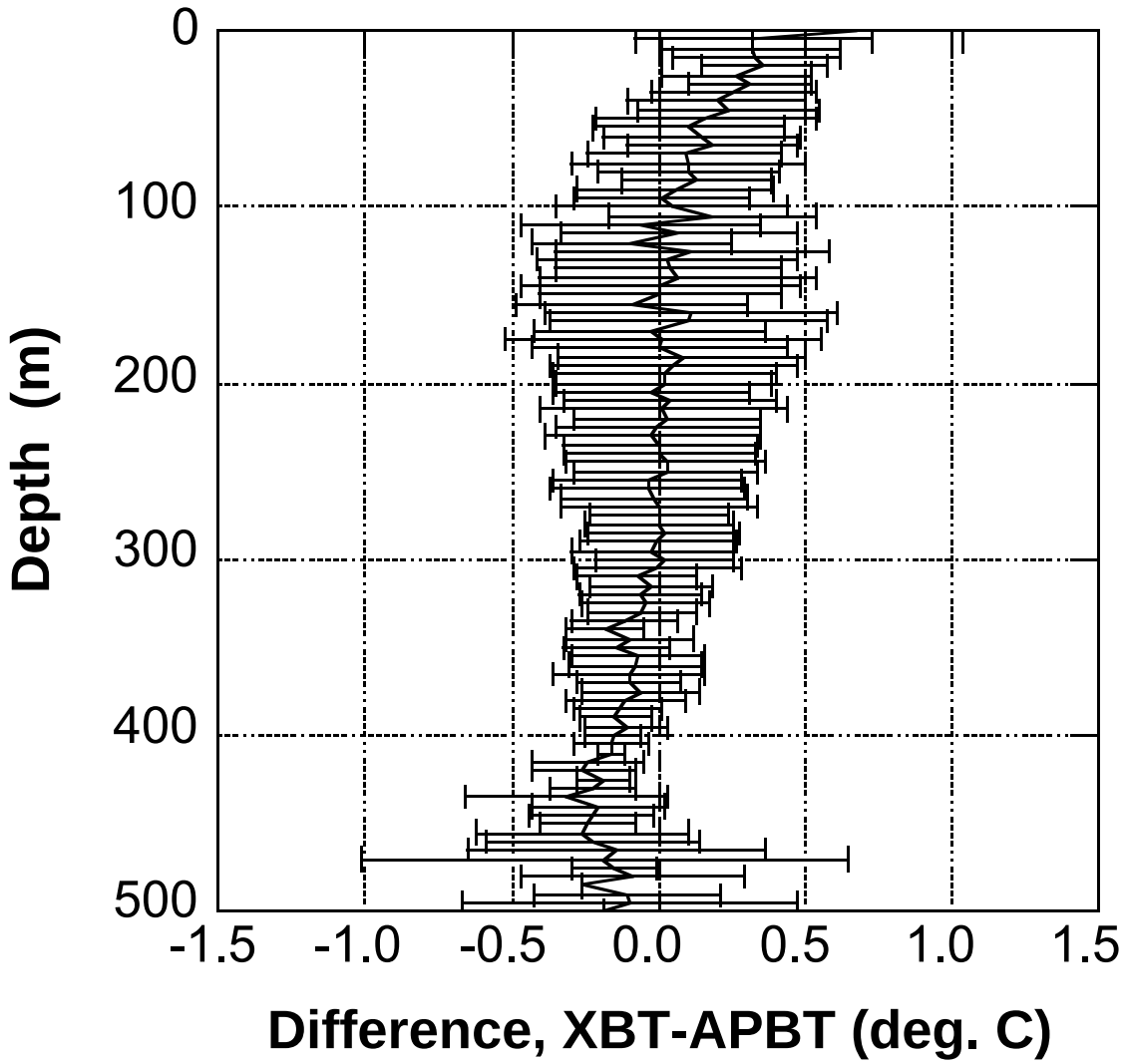

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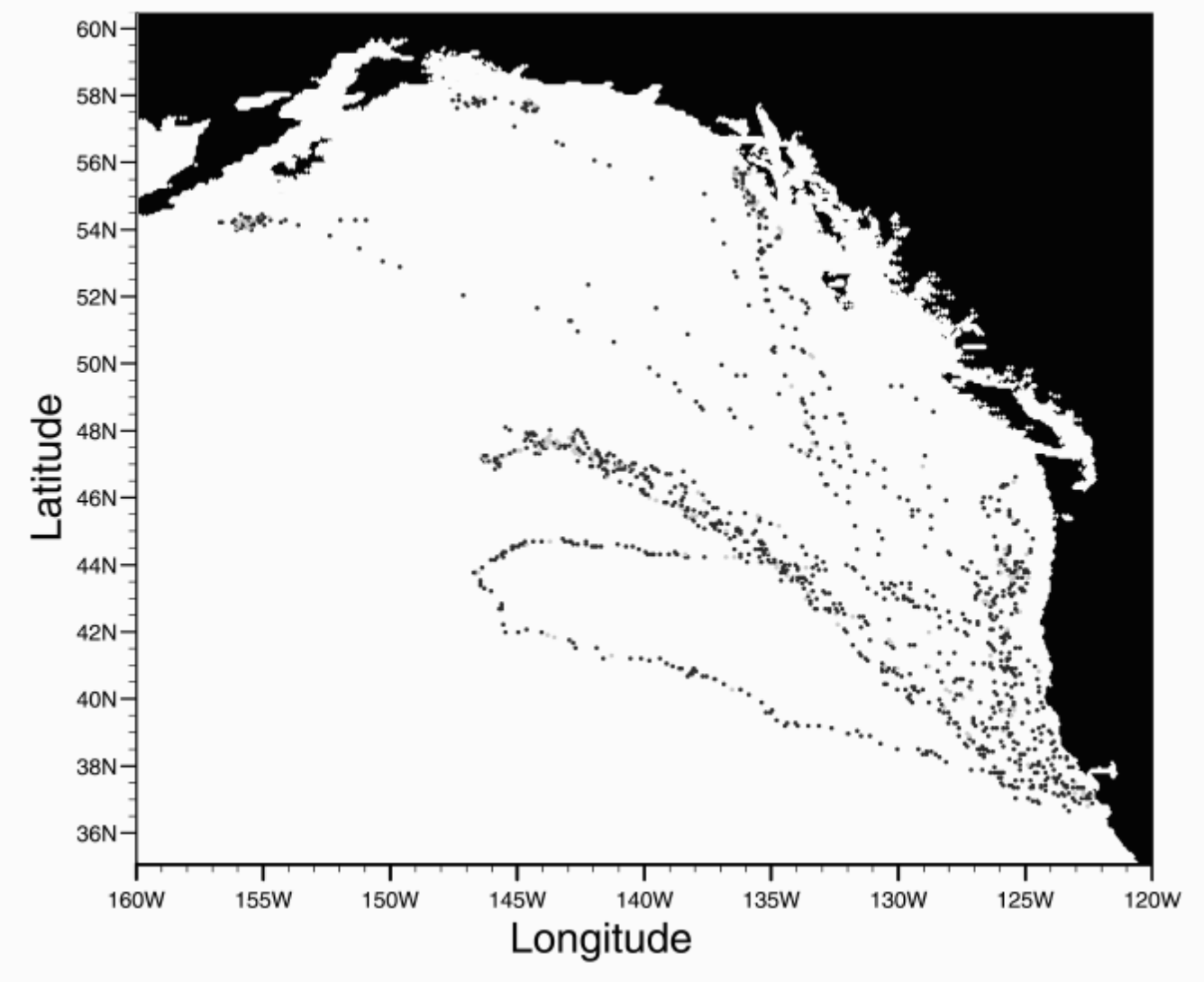

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