CSIRO

MARINE RESEARCH

A PILOT STUDY TO EXAMINE THE POTENTIAL FOR USING POP-UP SATELLITE TRANSMITTING ARCHIVAL TAGS (PATS) TO EXAMINE THE MIGRATIONS AND BEHAVIOUR OF ADULT SOUTHERN BLUEFIN TUNA (SBT)

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Table of Contents

List of Tables

List of Figures

Abstract

Nine Pop-Up Satellite Tags (PSAT) were deployed on large SBT (157-200cm FL) in the Tasman Sea from Australian commercial long-lining vessels during 2002-2003. Of the nine tags deployed, eight successfully reported back yielding 151 days of temperature and depth data in total. The longest attachment was 41 days and the shortest was 3 days. Premature release of PSAT was a problem with many tags detaching earlier than programmed. Therefore large scale movements were not observed. Further results and data collected from these tags are detailed in the paper.

1. Introduction

Southern bluefin tuna (*Thunnus maccoyyii*) are a highly migratory species, with the capacity to occupy a wide variety of pelagic habitats. Adult SBT spend several months from June to September in the waters of the south Tasman Sea where they are caught as by-catch by the domestic longline fishery when they target yellowfin tuna (YFT) and bigeye tuna. This region of the Tasman sea is characterized by dynamic oceanographic conditions, influenced by the Eastern Australian Current (EAC) and large eddies that are the result of warm water from the Coral Sea moving southward and meeting cooler sub-Antarctic waters (Nilsson et al., 1977; Nilsson & Cresswell, 1981). As a result, distinct temperature fronts form with large changes in water temperatures occurring over varying temporal and spatial scales (Nillson & Creswell, 1981). These oceanographic conditions are thought to dominate the distribution of tuna species in the region with YFT occupying the warm side of ocean temperature fronts and eddie cores (Young et al., 2001) and SBT being found on the cooler side (Gunn & Young, 1999). SBT, in common with the Pacific and Atlantic bluefin species, are able to occupy much cooler waters than tropical tunas such as skipjack and YFT (Gunn & Block, 2001) by utilizing specialized physiological adaptations such as cranial and visceral counter current heat exchange mechanisms (Gunn & Block, 2001). In this study we examine the utility of pop-up tags to describe the movement, temperature and depth preferences of SBT in the Tasman Sea in the winters of 2001 and 2002. The results are analyzed in relation to oceanographic conditions in the area.

2. Background and Objectives

The development and proving of pop-up tag technology has been underway at a handful of research labs around the world over the last two years, and as part of this international effort, CSIRO proposed in 1999 to undertake a pilot study on SBT using tags designed and manufactured in Seattle by Wildlife Computers Inc.

The objectives of the pilot study were:

1. Deploy 9 PAT's on sexually mature SBT during the NSW east coast winter season, scheduling these to pop-up at intervals ranging from 1-12 months.
2. Assess the quality of data collected by PAT's, in particular the position estimates produced by the on-board geolocation estimation software.

3. Determine whether each of these fish undertake a migration to the spawning ground in the 2000-2001 spawning season.
4. Determine when fish begin their migration from feeding to spawning grounds, and how long they spend on the spawning grounds.
5. Describe the habitat preferences (temperature and depth distributions) for each month at liberty.

3. Methods

Field Program in 2001

CSIRO scientists made four trips on commercial vessels to deploy tags on large and healthy SBT during the winter of 2001. Live SBT were caught on only one trip, and six fish were tagged. Table 1 gives the details of the releases and the positions and dates of each pop-up. The tagged fish were all considered to be alive and showed no sign of damage due to capture.

Fish were brought on board, following the methods developed and proven by Block and colleagues for Atlantic Bluefin tuna (see Block et al, 1998), and the titanium dart tag anchors were inserted into the dorsal musculature immediately adjacent to the second dorsal fin, again following as much as possible the methods of Block. A length measurement was taken and the fish released as soon as possible.

Our experimental design was to release fish with tags programmed to pop-up after times at liberty ranging from 1-6 months. The programmed dates for release are shown in Table 1. All tags were fitted with a "mortality trigger" – a device that allows the monofilament line that attaches the tag to its anchor to be cut if the fish goes below a predetermined depth. On the basis of data collected by the archival tagging work on SBT, and all the pop-up tagging of large adult Atlantic Bluefin, we assumed that if the tagged SBT descended below a depth of 1500m they had died, either as a result of tagging and handling, or from natural causes.

The tags were also programmed to recognize when they had detached from a fish and prematurely popped up to the surface. This is achieved by setting a time limit (in our case 48 hours) for depth readings shallower than a pre-determined depth (in our case 8m). When a tag has spent the allocated time above the depth limit, it begins transmission.

Field Program in 2002

A further 3 tags were released in 2002 (see Table 1) from a commercial longliner. The capture method used in 2002 differed slightly, in that hooked SBT were maneuvered into a large plastic chute before being hauled aboard the fishing vessel minimized the danger of injuring the eyes or gills. The chute served to restrain the tuna during tagging, making the correct placement of the tags easier and also increased the degree of control involved in returning fish to the water.

PAT Tag Data

Data transmitted by PAT tags are received by ARGOS receivers on NOAA satellites. Unfortunately, the ARGOS data transfer rates are too low to allow all of the data collected by the PATs to be transmitted, so Wildlife Computers PAT tags send three different types of transmit summarized data, - Time at Temperature (TAT), Time at Depth (TAD), and PAT Depth:Temperature (PDT). TAT and TAD data summarize the data at preprogrammed intervals, by calculating the proportion of time spent within depth or temperature ranges.

PAT Depth temperature (PDT) data is intended to represent the vertical structure of the water body that a fish inhabits. These data are generated by computing the maximum and minimum depths from the stored archival data over a user-defined period. The maximum and minimum temperature at these depths is also recorded. The tag then dynamically selects 6 extra depths between the maximum and minimum depths for a period, and similarly records the maximum and minimum temperatures. This is repeated every time the tag calculates the time at temperature and time at depth distributions.

The tags transmit an estimate of longitude and data from which estimates of latitude can be made for each day at liberty. The methods used to calculate latitude and longitude are described by Hill and Braun (2001). Briefly, longitude is determined by finding the time of midnight, defined as time at which the symmetry between dusk and dawn light curves is maximized. Latitude estimation was conducted using the Wildlife Computers PAT Geolocation software package (www.wildlifecomputers.com) that uses a set of nine light values selected by software on board the tag to represent the times around sunrise and another 9 values for sunset to determine the day length. The software matches the measured dawn and dusk light curves to theoretical curves generated for different latitudes. The latitude that generates curves that best match the observed dawn and dusk curves is judged to be the best estimate of Latitude (Wildlife Computers, 2001).

By comparing the pop-up positions, estimated with a high degree of accuracy by ARGOS, with the geolocation pop-up positions, we were able to make a limited assessment of the genuine error involved in the geolocation process. The error in the estimates was broken into three components: the distance on the globe from the two positions, the distance from latitudes alone assuming constant longitude, and the distance between the longitudes assuming constant latitude (33^{o} S was used).

4. Results

Six tags were deployed in 2001 and three in 2002. All of those released in 2001 successfully transmitted data back to CSIRO after varying times attached to fish. Two of the three 2002 releases transmitted data. The data transmissions lasted on average 12 days, and in most cases data were of a high quality. We are therefore satisfied that the repetition rates used in our data transmission protocols were adequate for the range of weather\sea state conditions experienced in the Tasman Sea during winter.

The pop-up times for all but one of the tags were earlier than we had planned and programmed into the tags. There appear to be two reasons for premature pop-up and transmission of data – mortality of the tagged fish and tag shedding. Two tags (00-233 and 00-P0973) popped up after the mortality trigger was activated. These fish appear to have lived for 3 and 5 days respectively, after capture and tagging. The maximum depth data showed last depths of around 1000m (Figure 8). Both fish were alive and in excellent condition when tagged and released with no obvious bleeding or problems due to capture and handling. In similar studies over seas by Dr Barbara Block[1] and associates, post-release mortality of medium and giant sized Atlantic bluefin tuna have been very low following capture by hook and line recreational fishing.

General Movement

The displacement from release to pop-up positions showed no common directional movement (Figure 1 & Figure 3). The displacement of the fish varied considerably and the longest attachments did not produce the greatest displacements. The releases in 2002 were attached longer than those in 2001, yet one 2002 pop-up position was very close to the release position after 26 days (Figure 3). All of the fish were expected to be reproductively mature therefore longer attachments may reveal a more consistent pattern of displacements as adult fish in the Tasman Sea may travel to the Indonesian spawning grounds south of Java (though there is no data on whether adult SBT return to the spawning grounds annually or more intermittently). The last tag to pop-up in 2002 (00-P0971) transmitted from well south of the EAC (Figure 11) unlike the other tags. This may indicate this particular fish starting to move away from the Tasman Sea, perhaps en route to the spawning grounds or back to the southern ocean feeding areas.

All tags popped up in similar water masses to those they were released in (Figure 10-13). All fish were caught and released in similar temperature water (approximately 20^{o}C) (Figure 2 & Figure 4). In 2001, all the tagged fish were caught on the Eastern side of the core of the EAC in what appears to be more variable Sea Surface Temperature (SST) conditions than on the western side of the EAC jet. The 2002 releases were to the west of the core of the EAC but in similar temperature water. Fishing operations utilized regularly updated SST images and water of this nature was targeted. Skippers reported setting lines across intermingling water masses.

Depth and Temperature Preference

Figure 5 shows the distribution of depth preferences, for individual SBT and across the aggregated data. A large proportion of the time (approximately 35%) was spent in surface waters (0-15m), but a preference for deeper waters is also indicated. This results in a bi-modal aggregated depth distribution (Figure 5b), with a peak in the surface waters and another flatter distribution with a mode in the 300m bin.

[1] Dr. Barbara A. Block, Hopkins Marine Station, Pacific Grove, California, U.S.A

While a preference for surface waters is obvious, the time-at-depth bins we chose for these trial deployments did not allow us to determine whether there is diurnal variability in depth preferences, as has been shown in juveniles SBT when they are in oceanic waters (Gunn & Block, 2001) and bigeye tuna (*Thunnus obesus*) (Holland et al, 1991; CSIRO, unpublished data).

Although all fish spent a large amount of time in the upper 15 m of the water column, there was significant variation among individuals in the time spent at depths below 15 m. Some fish displayed an even spread of habitation across the depth ranges (eg. SBT 00-237 - Figure 5a) while others showed strongly bimodal distributions. As a result of the bimodal depth distribution, the temperature preference data showed two peaks; one at approximately 20^{o}C and a cooler mode at around 15^{o}C. The degree to which individual fish contributed to each mode of the temperature distribution varied (Figure 6). Notably, the depth encompassing most of the data is relatively deep. For example the cumulative distribution give in Figure 5b shows that the depth must be approximately 300m to encompass 98% of the data.

From this data alone, it is difficult to determine if the bi-modal temperature distribution seen in Figure 6 is solely the result of bi-modal depth preference or as a result of moving across frontal zones, or a combination of both possibilities. To explore this possibility further we examined the PDT data and constructed vertical temperature/depth profiles by plotting the minimum temperature at each PDT depth against the PDT depths (Figure 7). Plots of the PDT data split as a time series for both temperature and depth are also shown (Figure 8 & Figure 9). Figure 7 shows that there was a fair degree of variability in temperature for a given depth. This suggests that several SBT were moving through different bodies of water rather than trying to remain within waters of a particular temperature. In particular, the depth/temperature profiles for tags (ARGOS numbers 28707, 28709, 13272) show several merged temperature depth profiles. Markedly different temperatures were sampled at the same depths, suggesting that the fish are moving between different water masses. What cannot be determined from this data directly is the residence time of SBT in particular water masses.

It is worth noting that tag (PTT 13275) appears to give erroneous temperature readings. The depth/temperature plot apparently recorded temperatures as high as 25^{o}C at approximately 600m. This is completely implausible and appears to be a sensor malfunction. Examining the plots of temperature through time (Figure 9) for this tag suggest that for a period toward the end of the deployment a sudden unexplained increase in minimum PDT temperatures occurred from approximately August 8 2002 onwards. Again, this suggests that this particular tags temperature sensor was not working correctly. These data also influence the warmest (right hand) tail of the temperature distribution in Figure 7.

The maximum depth data (Figure 8) show that the tagged SBT made regular deep dives and often descended to depths over 400m. This seems to suggest that adult SBT are capable of utilizing much of the water column while foraging. There was no apparent relationship between maximum depth and size. Furthermore from the available PAT data there was no relationship between maximum depth and the hour that the summaries took place. This is the only way to look for temporal patterns in this data, however, it should be noted that this does not preclude a strong diurnal component to diving behaviour. Rather, the conclusion is that this particular sampling configuration was not able to detect daily diving patterns.

The plots of PDT temperature through time (Figure 9) suggest the fish rarely ventured into waters much warmer than $20^{o}C$. This appeared to be the case for all deployments and is consistent with the temperatures at release. The temperature histograms in Figure 6 also reinforce this conclusion with very few readings in the warmer temperature categories. Some of the readings in these warmer temperature categories are presumably due to tag sensor errors.

Discussion

Tag Performance

The performance and operation of the tags was generally very good. All but one tag transmitted reliably and only 1 major sensor failure was seen in the data. There were apparent outliers in the temperature data from all tags. The reasons for this are unclear, but it should be noted that on the model of PAT used, the thermistor is housed within the body of the tag perhaps increasing the number of erroneous temperature readings as the thermistor cannot respond to quick changes in temperature accurately. The prototypes of the next generation of Wildlife PATs is not expected to suffer this problem to the same degree as the thermistor is located on the exterior of the tag (Dr R. Hill[2], pers. Comm.).

The failure of the third 2002 PAT to transmit is impossible to explain conclusively. Tag electronic failure is a possibility, but given consistent performace by all the WC PAT tags we've used over the last two years, seems unlikely. Predation on the tagged fish and destruction of the tag is a possibility. "Predation" on a floating or ascending PAT tags has been observed by Gunn et al. (submitted) in the Coral Sea, where the tags were taken to depth of up to 650m, most likely by squid, before being released and returning to the surface. Fouling is also a possibility, although this has not been a problem for any SBT archival tags that we have had returned over the last eight years.

The attachment of PATs for long periods remains a major challenge. The 2001 releases in this study, suffered particularly badly from early releases. The three tags released in 2002 were better, but of the two tags that transmitted data, only one released on time. The other tag released 12 days early. The substantial improvement seen in 2002 may well be a result of improving the methods for getting the fish aboard and better tag placement.

Despite the attachment problems the tags did return sizeable amounts of valuable data on the habits of adult SBT. At this stage these tags offer the best tool to gather movement and behavioural data on adult SBT.

[2] Dr Roger Hill, Wildlife Computers, Redmond WA., USA.

Habitat Preference of SBT in the Tasman Sea

Overall, adult SBT in the Tasman Sea appeared to prefer deeper water than has been found in other bluefin species. While the fish tagged spent around 40% of their time in surface waters (<7m), approximately 90% of the time observed was in waters less than 300m deep. This appears different to Pacific bluefin that spend over 80% of the time in the top 40m (Marcinek et al, 2001). Furthermore, Lutcavage et al. (2000) found that adult Atlantic bluefin spent more than 90% of their time in the top 30m. Kitagwa et al., (2002) found that juvenile Pacific bluefin, implanted with archival tags, in the East China sea were fairly surface oriented with a mean depth of 120m and few dives deeper than 300m. Similarly, juvenile southern bluefin tuna appear to be much more surface oriented (Gunn & Block, 2001) than is suggested by the data presented here. The reasons for these differences are unclear, but we could hypothesize that deeper depth preference is mediated by the unusual oceanographic conditions. Perhaps a deeper mixed layer in the EAC allows for deeper diving by creating favourable thermal conditions much deeper than has been seen in other studies. Adult SBT may have more efficient thermal conservation mechanisms than juveniles. However, the range of water temperatures considered in this study does not differ markedly from those experienced by juvenile SBT. Therefore this seems to be an unlikely explanation of the data. However, no observations of visceral temperature of large SBT have been gathered so this explanation cannot be ruled out.

A further possibility is that the waters of the EAC are in fact warmer than is generally preferred by large SBT. Except for when spawning and in the Tasman, adult SBT are generally found in cold Southern ocean waters. Therefore the deep dives observed and crossing between warm eddy zones across thermal fronts may in fact be a behavioural mechanism that enables heat loss. We would hypothesize that similar behaviour would be observed during spawning episodes in the northeast Indian Ocean where surface temperatures exceed 30^{o}C.

The PDT data suggested that the fish make deep dives (>400m) on a regular basis and also spend most of their time in water temperatures between 10 and 20^{o}C. However the temperature distributions showed that there was a bi-modal distribution of temperature preference within this region. The cumulative distribution of temperatures in Figure 6 shows that the SBT spent approximately 96% of their time in waters less than 21^{o}C, but only 9% of their time in waters less than 15^{o}C. This suggests a reasonably narrow temperature preference in the frontal edges with SBT making excursions into waters both warmer and cooler than this range.

Therefore, it is necessary to examine the availability of the habitat (i.e. temperatures within 15-21^{o}C) with respect to depth. To do this we examining synthetic bathythermograph output from the CARS (CSIRO Atlas of Regional Seas) dataset (Ridgway et al., 2002) at the time of release. As an example, two slices, one inshore and one offshore are considered for the July 27 2002 (Figure 12). It can be seen that the Tasman Sea at this time was dominated by a large eddy structure centered at around 35^{o} 5'S 152^{o} 5'E. This can also be seen in the satellite altimetry structure (Figure 12b). Synthetic bathythermograph data was then extracted along each of the inshore and offshore slices (Figure 12a) to give an indication of the depth of the mixed layer (MLD) at these regions (Figure 12 c & Figure 12d). Outside of an eddy, the MLD was approximately 100-150m deep and descends to a depth of around 400m in the eddy core. Furthermore, the range of temperatures sampled by the tags (15-20^{o}C) extends much deeper in the interior of the eddy compared to the frontal zones. This means that within a front SBT could dive deep and still be in relatively warm water.

It is important to note that temperature is not the only factor that is driving the results seen here. The foraging ecology associated with frontal zones is likely to be a large determinant of the behaviour observed. Young et al. (2001) found that fronts in the Tasman sea serve to concentrate food and that YFT feed on slope and shelf attached prey species on the western side of EAC eddies. Catch-per-unit-effort figures also corroborated this explanation with high catches being recorded in these areas. Young et al (1997) found that there were differences in the diet of juvenile SBT caught in and out of the EAC of eastern Tasmania.

Conclusions

- Reliable tag attachment remains an impediment to gathering long-term data sets and fully exploiting the potential of satellite tag technology.

- The use of a chute to bring SBT aboard fishing vessels and to facilitate more accurate tag placement appeared to result in longer attachments and better success than experienced in 2001.

- PAT tags were able to reliably transmit data and withstand winter sea state conditions in the Tasman sea

- Adult SBT appear to spend a greater proportion of time deeper than has previously been observed. Longer attachment periods may determine if this is a phenomenon specific to EAC waters.

- Deeper than previously observed depth distributions could be explained in several ways. Favorable thermal conditions extending deeper than other parts of their range may enable a greater proportion of time to be spent quite deep. Alternatively this behaviour may reflect the ability of larger SBT to remain at depth longer than juvenile SBT previously observed. The excursions into cooler water may indicate that the fish are venturing into cooler water to lose heat.

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References

Arnold, G. & Dewar, H. (2001) in Sibert, J.R. & Nielsen, J.L. (eds.) Electronic Tagging and Tracking in Marine Fisheries. Proceedings of the Symposium on Tagging and Tracking Marine Fish with Electronic Devices, February 7-11, 2000, East-West Center, University of Hawaii. Kluwer Academic Publishers. Netherlands. 468pp.

Block, B.A., Dewar, H., Farwell, C. and Prince E.D. (1998) A new satellite technology for tracking the movements of Atlantic bluefin tuna., Proc. Natl. Acad. Sci., USA. 95: 9384-9389.

Graves, J.E., Luckhurst, B.E. and Prince, E. D. (2002) An evaluation of pop-up satellite tags for estimating postrelease survival of blue marlin (*Makaira nigricans*) from a recreational fishery. Fish. Bull. 100(1): 134-142

Gunn, J. S. & Block, B. A. (2001) in Block, B.A. & Stevens (eds.)Tuna: Physiological Ecology and Evolution (A Volume in the Fish Physiology Series). Academic Press. 469pp.

Gunn, J.S., Patterson, T. A. and Pepperell, J.P. (Submitted) Short-term movement and behaviour of black marlin *Makaira indica* in the Coral Sea determined through a pop-up satellite archival tagging experiment. Marine and Freshwater Research.

Gunn, J.S. & Young, J.W. (1999) Environmental Determinents of the movement and migration of juvenile southern bluefin tuna in Hancock, D.A., Smith, D.C. & Koehn, J.D. (eds.) Fish Movement and Migration. Australian Society for Fish Biology Workshop Proceedings. Bendigo, Victoria 28-29 September 1999.

Hill, R.D and Braun, M.J. (2001) Geolocation by Light Levels – the Next Step: Latitude in Sibert, J.R. & Nielsen, J.L. (eds.) Electronic Tagging and Tracking in Marine Fisheries. Proceedings of the Symposium on Tagging and Tracking Marine Fish with Electronic Devices, February 7-11, 2000, East-West Center, University of Hawaii. Kluwer Academic Publishers. Netherlands. 468pp.

Holland, K. N., Brill, R. W., Sibert, J.R. & Fournier, D. A. (1992) Physiological and behavioural thermoregulation in bigeye tuna (*Thunnus obesus*). Nature 358: 410-412.

Kitagawa T., Nakata, H., Kimura, S., Sugimoto, T. and Yamada, H. (2002) Differences in the vertical distribution and movement of Pacific bluefin tuna (*Thunnus thynnus orientalis*) among areas: the East China Sea, the Sea of Japan and the western North Pacific. Mar. Freshwater Res. 53: 245-252.

Lutcavage, M., Brill, R., Porter, J., Howey, P., Murray, E., Mendillo, A., Chaprales, W., Genovese, M., and Rollins, T. (2000). Summary of pop -up satellite tagging of giant bluefin tuna in the joint US-Canadian program, Gulf of Maine and Canadian Atlantic. ICCAT, SCRS/00/95, 9 pp. (mimeo.).

Marcinek, D.J., Blackwell, S.B., Dewar, H., Freund, E.V., Farwell, C., Dau D., Sietz, A. C. & Block, B.A. (2001) Depth and muscle temperature of Pacific bluefin tuna examined with acoustic and pop-up satellite tags. Marine Biology 138: 869-885.

Musyl, M.K., Brill, R.W., Curran, D.S., Gunn, J.S., Hartog, J.R., Hill, R.D., Welch, D.W., Eveson, J.P., Boggs, C.H. & Brainard, R.E. (2001) Ability of Electronic Archival Tags to Provide Estimates of Geographical Position Based on Light Intensity in Sibert, J.R. & Nielsen, J.L. (eds.) Electronic Tagging and Tracking in Marine Fisheries. Proceedings of the Symposium on Tagging and Tracking Marine Fish with Electronic Devices, February 7-11, 2000, East-West Center, University of Hawaii. Kluwer Academic Publishers. Netherlands. 468pp.

Nillson, C.S., Andrews, J.C., & Scully-Power, P. (1977) Observations of Eddy Formation off East Australia. Journal of Physical Oceanography.

Nilsson, C.S. & Cresswell, G.R. (1981) The Formation and evolution of East Australian Current warm-core eddies. Progress in Oceanography 9:133-183.

Ridgway, K.R., Dunn, J.R. & Wilkin, J.L. (2002) Ocean Interpolation by Four-Dimensional Weighted Least Squares – Application to the Waters around Australasia. Journal of Ocean and Atmosphere Technology 19(9): 1357 – 1375.

Pepperell, J. G., and Davis, T. L. O. (1999) Post-release behaviour of black marlin *Makaira indica*, caught off the Great Barrier Reef with sportfishing gear. Marine Biology 135(2): 369-380

Young, J. W., Lamb, T.D., Duyet Le, R., Bradford, R. W. & Whitelaw, A. W. (1997) Feeding ecology and interannual variations in diet of southern bluefin tuna, *Thunnus maccoyii*, in relation to coastal and oceanic waters of eastern Tasmanian, Australia. Environmental Biology of Fishes 50:275-291.

Young, J.W., Bradford R., Lamb, T D., Clementson, L. Closer, R. & Galea, H. (2001) Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes. Mar. Freshw. Res. 52(4):463-474.

Wildlife Computers (2001) Wildlife Computers Geolocation Programs User's Guide. Wildlife Computers. Redmond, U.S.A.

Table 1. Release and pop-up details for all PAT tags released.

Release Date	Release Position	PTT	TAG#	LCF (cm)	Estimated Weight (kg)	Pop-Up Date	Pop-Up Position
PAT deployments in the Tasman Sea, July 2001							
13-Jul-01	33°25'S 151°33'E	28703	00-233	170	94	16-07-01	33°23'S 151°51'E
13-Jul-01	35°14'S 151°32'E	28708	00-238	158	73	27-07-01	37°26'S 156°37'E
13-Jul-01	35°13'S 151°32'E	28707	00-237	190	137	07-08-01	37°19'S 154°7'E
13-Jul-01	35°35'S 151°36'E	13275	00-P0974	200	164	13-08-01	33°43'S 153°7'E
13-Jul-01	35°53'S 151°34'E	28701	00-231	175	104	19-07-01	35°54'S 153°1'E
15-Jul-01	35°36'S 151°36E	13274	00-P0973	178	110	20-07-01	35°10'S 152°26'E
PAT deployments in the Tasman Sea, July 2002							
27-Jul-02	35°1'S 151°39'E	28709	00-239	157	72	22-8-2002	35°4'S 152° 41'E
27-Jul-02	35°05' S 151°39'E	13272	00-0971	173	100	6-09-2002	36°49'S 152°6'E
27-Jul-02	35°7' S 151°40'E	20926	02-0218	173	100	Failed to transmit data	

Table 2. Estimates of final position from ARGOS satellites and from geolocation algorithms. Note that for tag 00-237, the geolocation on the pop-up date was unusable so a position from the previous two days has been used.

Tag		Date	Latitude (°S)	Longitude (°E)	Geolocation Date	Geolocation Latitude (°S)	Geolocation Longitude (°E)
00-P0973	Release	13-Jul-01	-35.6	151.6	15-Jul-01	-34	150.70
	Pop-up	20-Jul-01	-35.6	152.98	19-Jul-01	-22	152.90
00-P0974	Release	15-Jul-01	-35.58	151.6	15-Jul-01	-25.5	151.87
	Pop-up	13-Aug-01	-33.7	153.02	13-Aug-01	-20.5	153.20
00-231	Release	13-Jul-01	-35.88	151.5667	15-Jul-01	-35	143.65
	Pop-up	19-Jul-01	-35.9	153.01	19-Jul-01	-36	152.98
00-233	Release	13-Jul-01	-35.42	151.55	14-Jul-01	-33	166.99
	Pop-up	16-Jul-01	-33.3	151.85	16-Jul-01	-36	-167.31
00-237	Release	13-Jul-01	-35.22	151.5333	14-Jul-01	-33	166.99
	Pop-up	7-Aug-01	-37.3	153.85	03-Aug-01	-39.5	152.67
00-238	Release	13-Jul-01	-35.23	151.5333	14-Jul-01	-33	166.99
	Pop-up	27-Jul-01	-37.4	156.76	25-Jul-01	-28.5	159.12

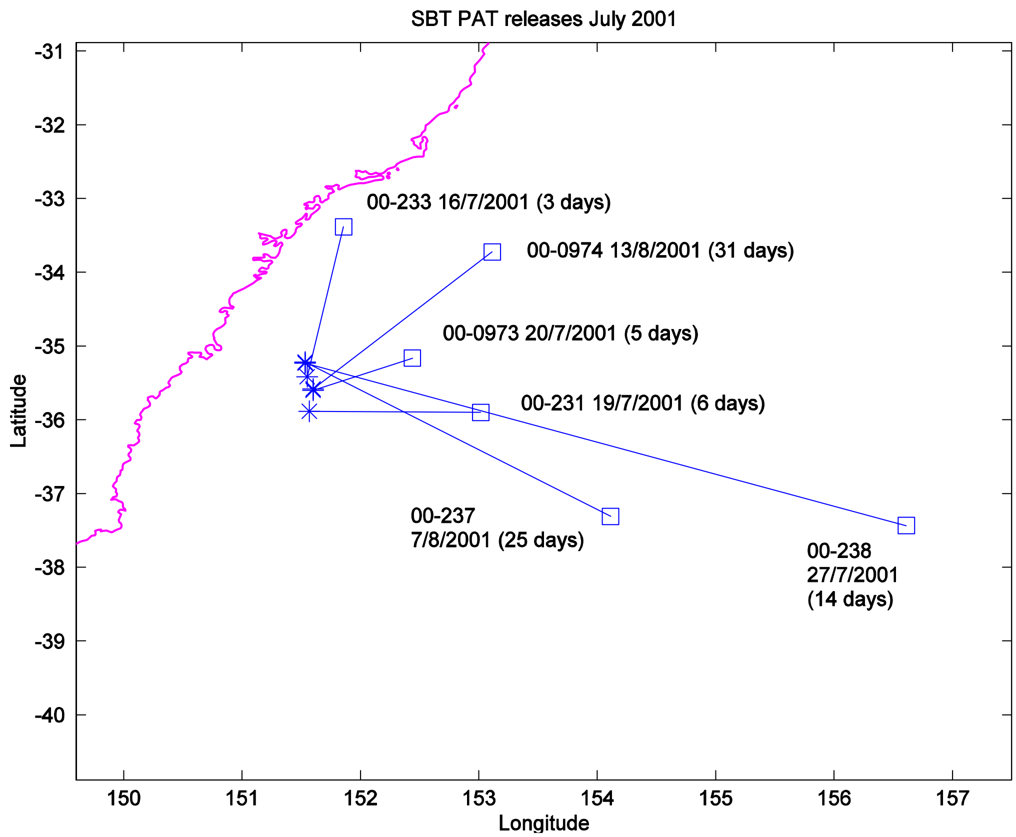


Figure 1. 2001 PAT releases (asterisk) and pop-up points (squares). The captions show the tag number, the pop-up date and the days between release and pop-up in parentheses.

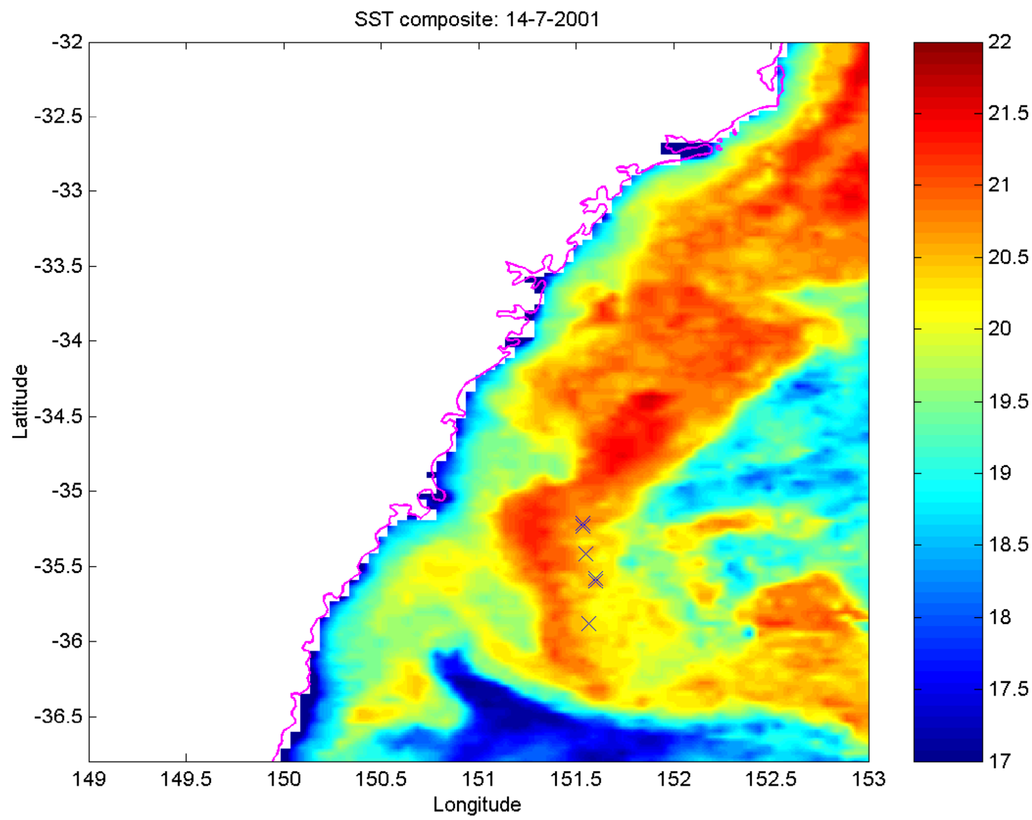


Figure 2. 3-day composite of SST data at release of the 2001 popup tags. Release points are marked with crosses (X). The composite SST data is for the 13-15 July 2001.

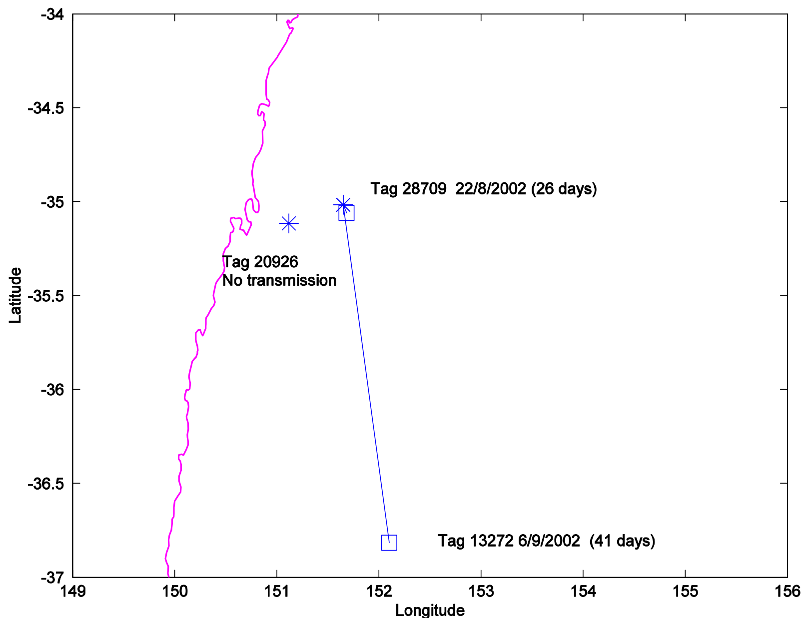


Figure 3. 2002 PAT release and pop-up position. The captions give the tag number, pop-up date and the time between release and pop-up in parentheses. Note that tag 28708 released very close to the deployment position 28 days after release.

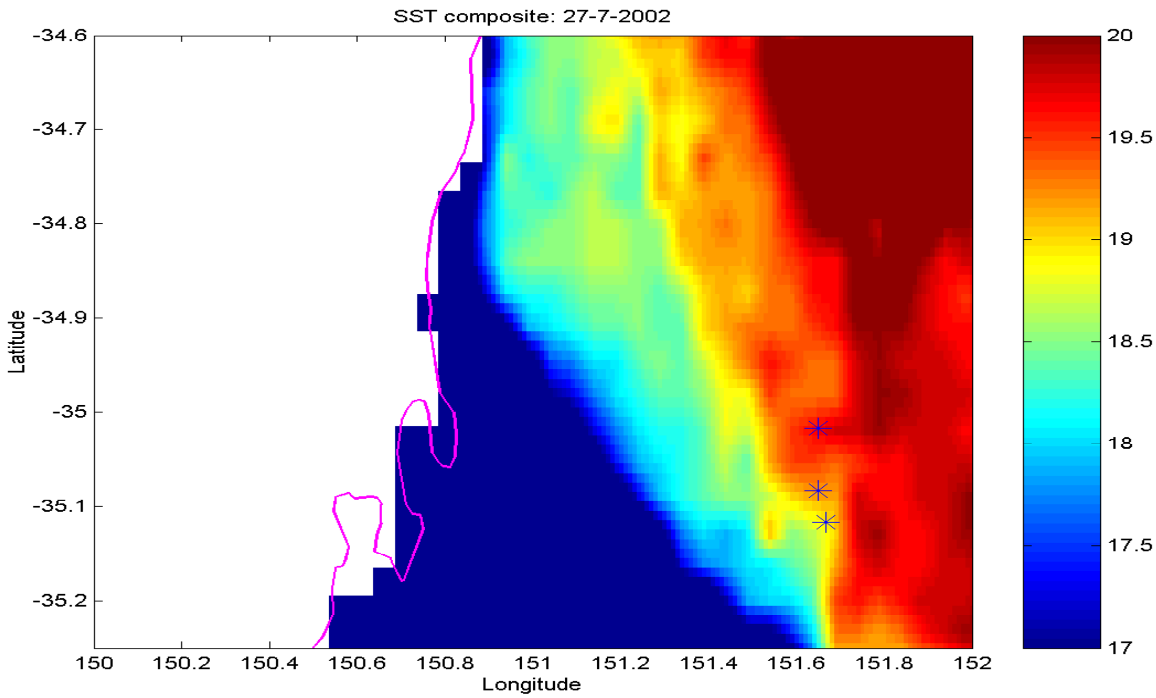
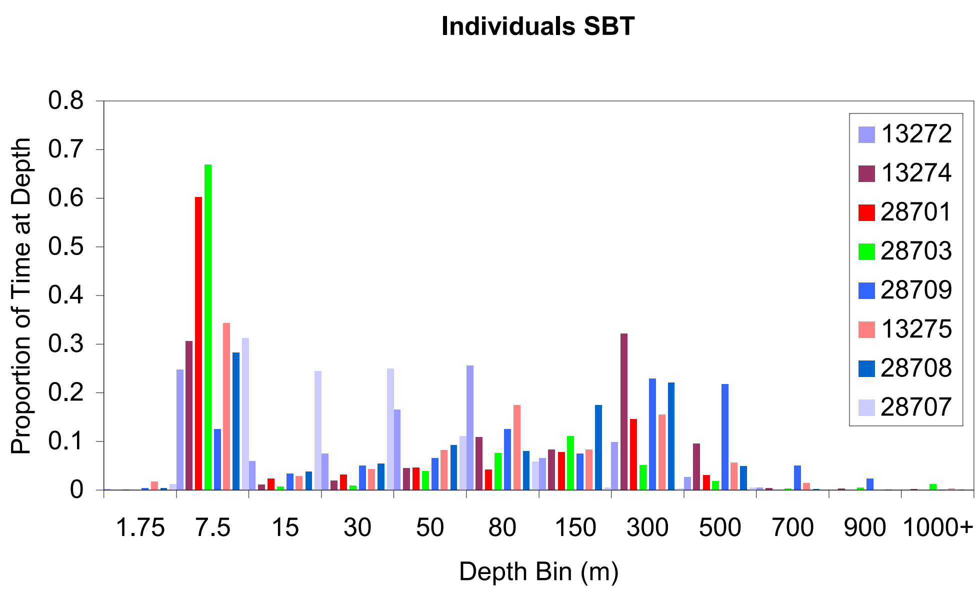


Figure 4. Deployment locations and SST composite data for July 25 – 28 2002. The tags were deployed on July 27.



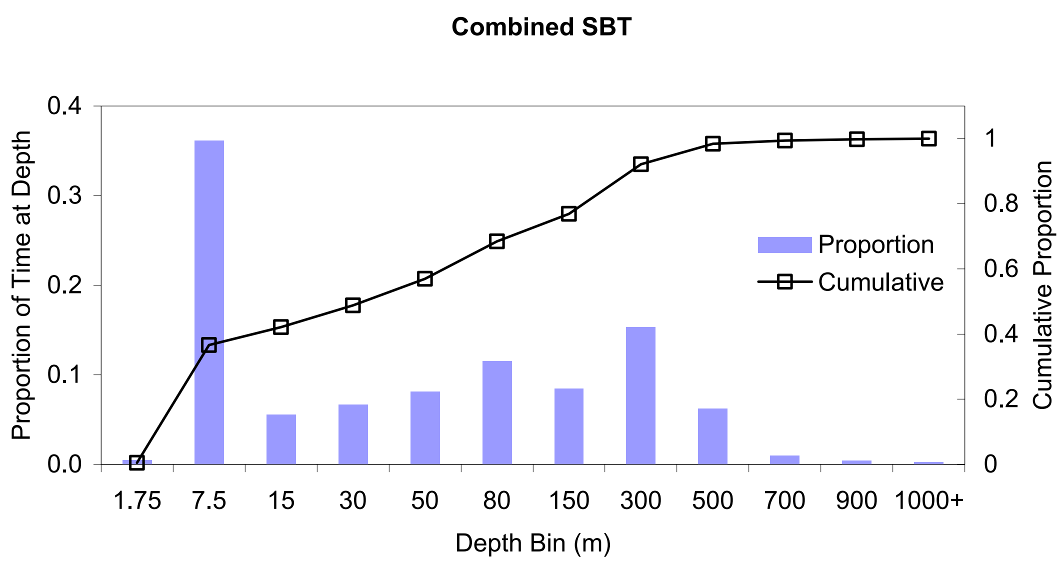
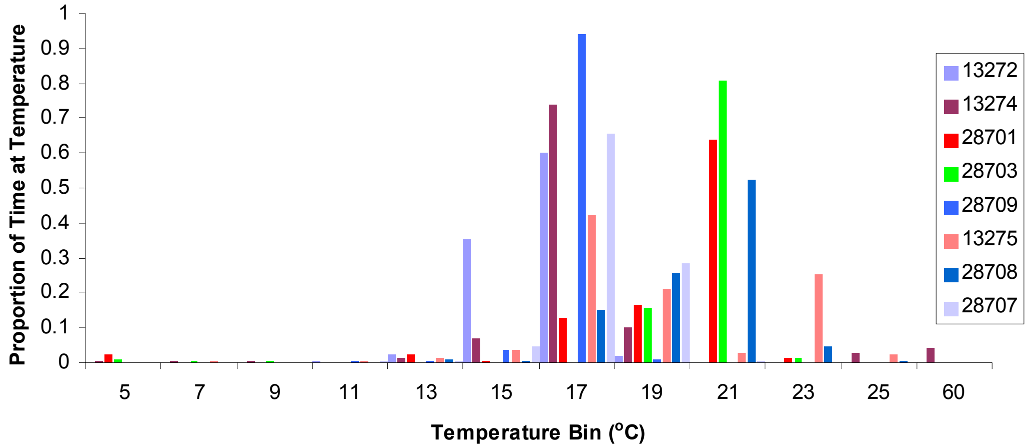


Figure 5. (a) Individual Depth Distribution from 8 SBT. (b) Depth distribution from aggregated data with the cumulative proportion of time at depth given on the right hand axis.



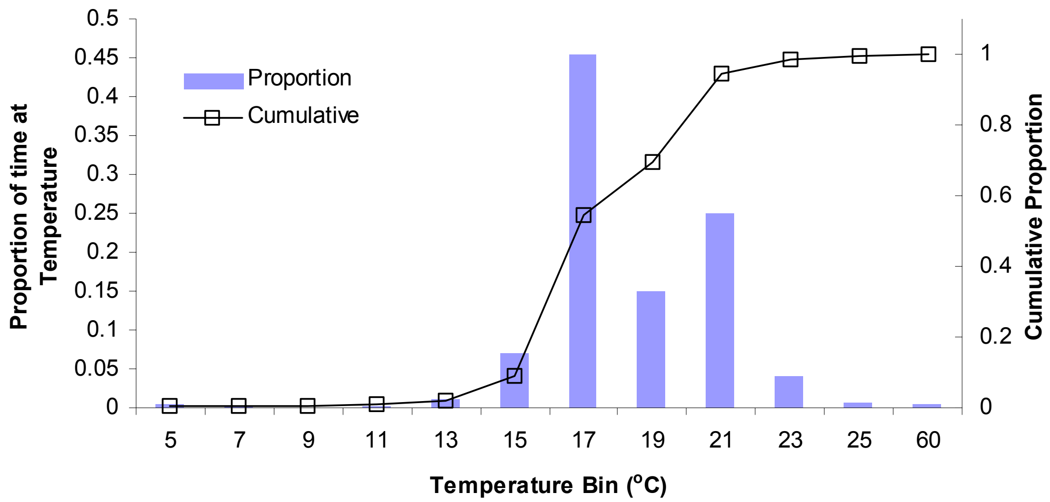


Figure 6. (a) Proportion of time at temperature for all 8 SBT (b) The proportion of time at temperature aggregating the data

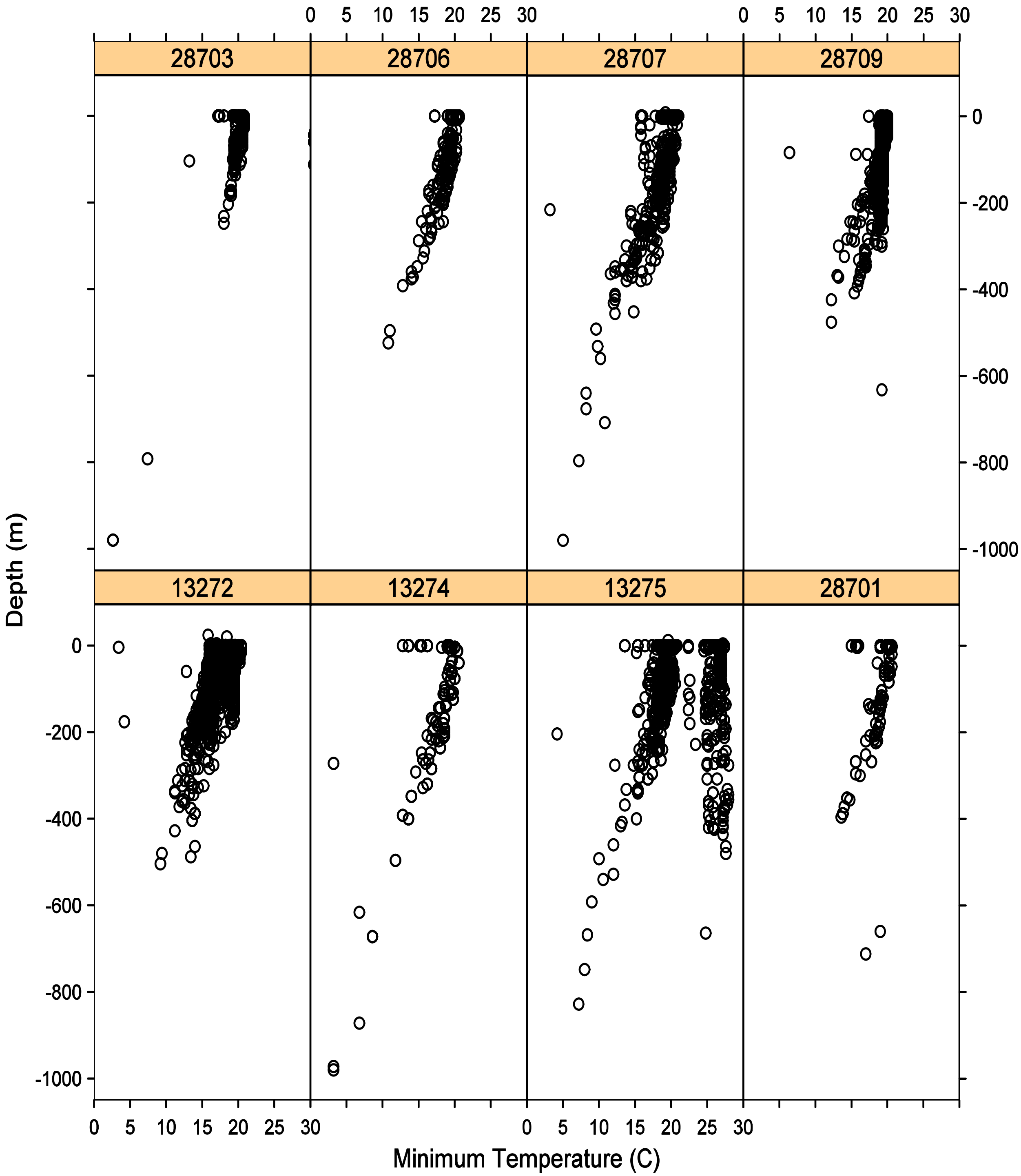


Figure 7. Depth vs Temperature profiles for each tag (PTT numbers are given in this plot – refer to Table 1 for the associated tag numbers).

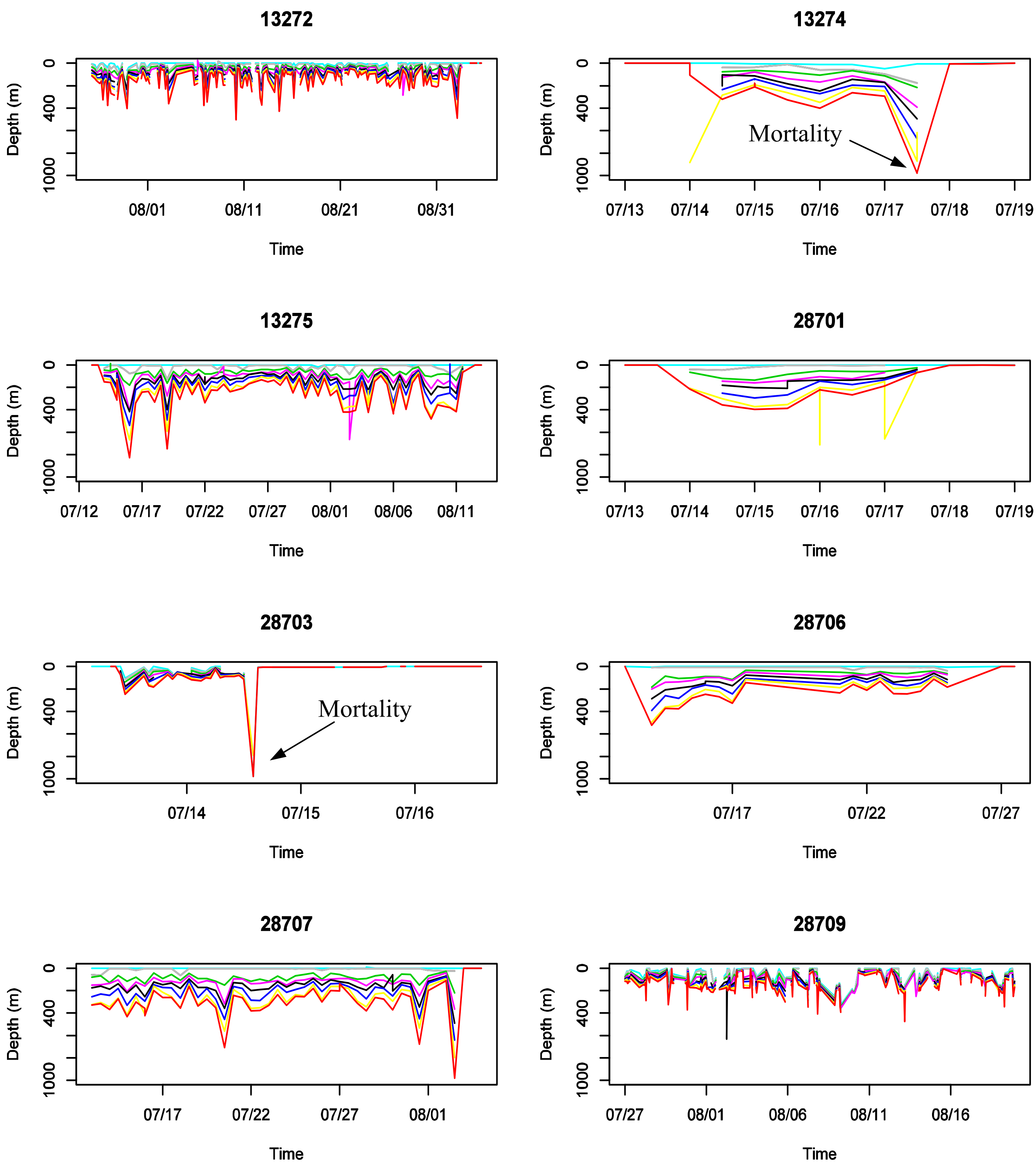


Figure 8. PAT PDT depth data for all 8 tags deployed in 2001-2002.

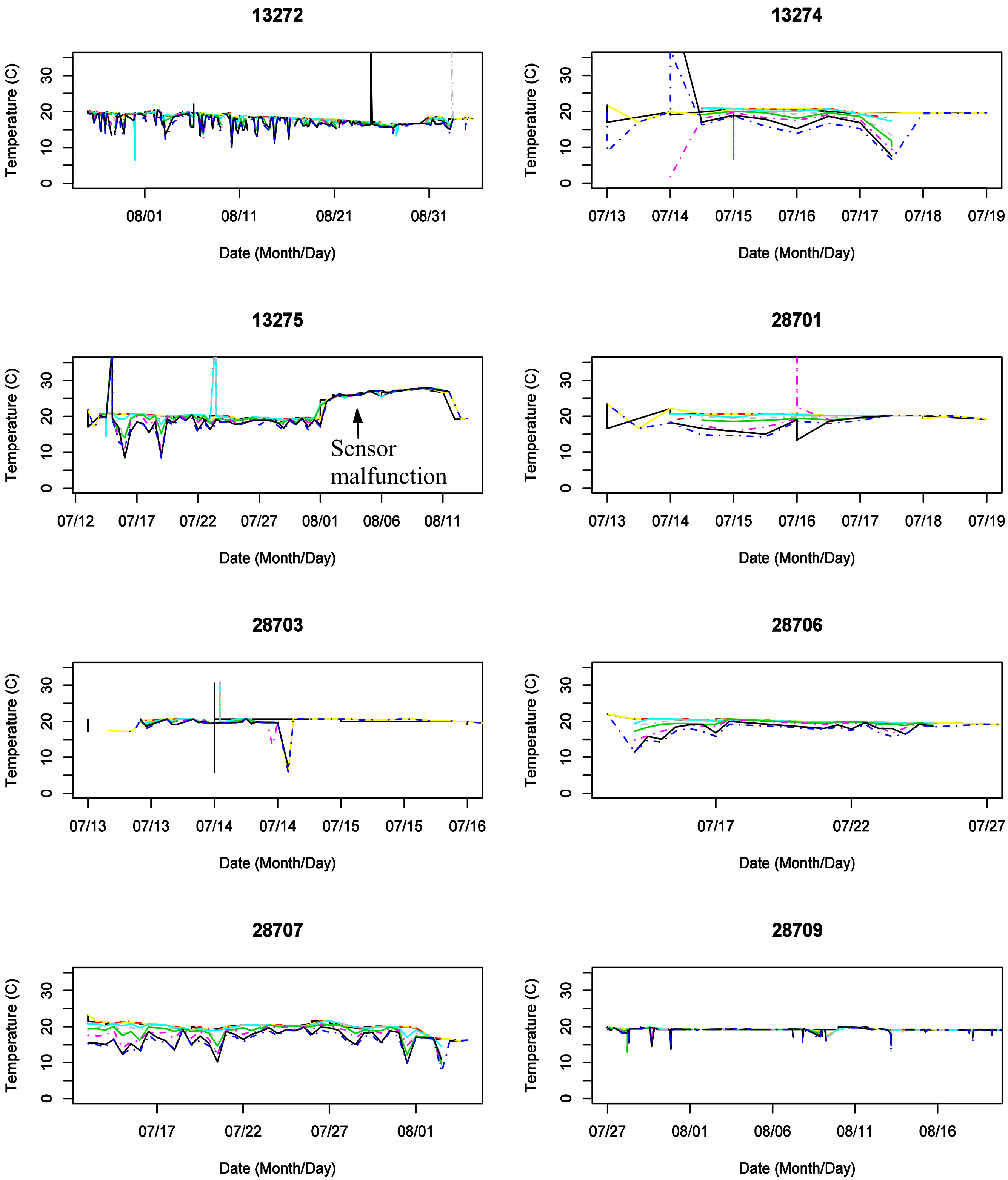


Figure 9. PDT minimum temperatures for each tag.

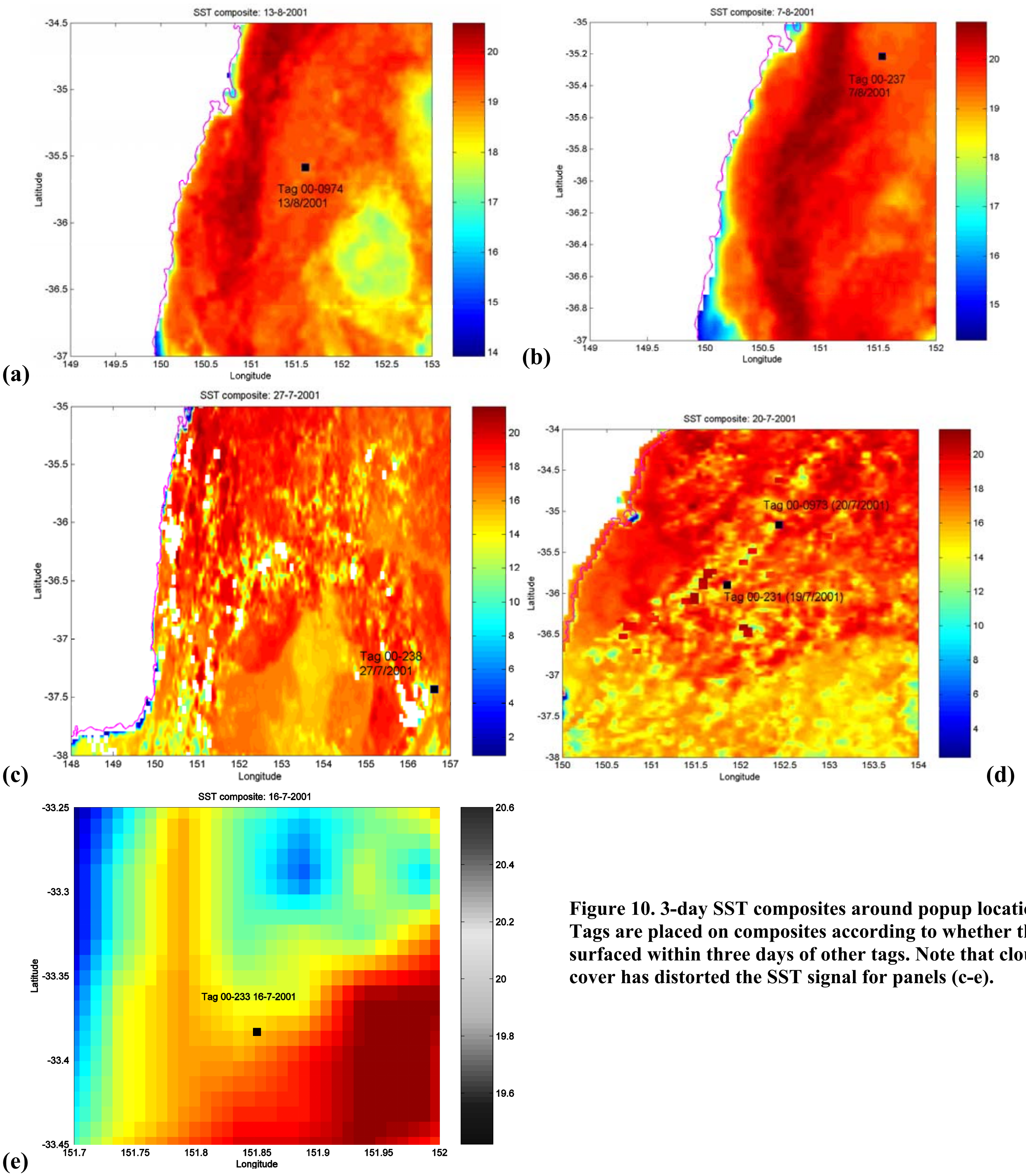
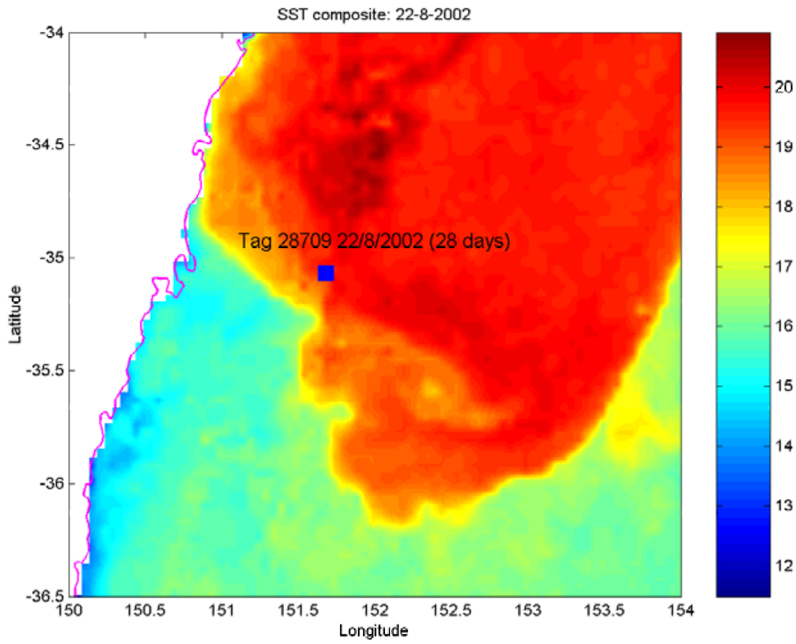
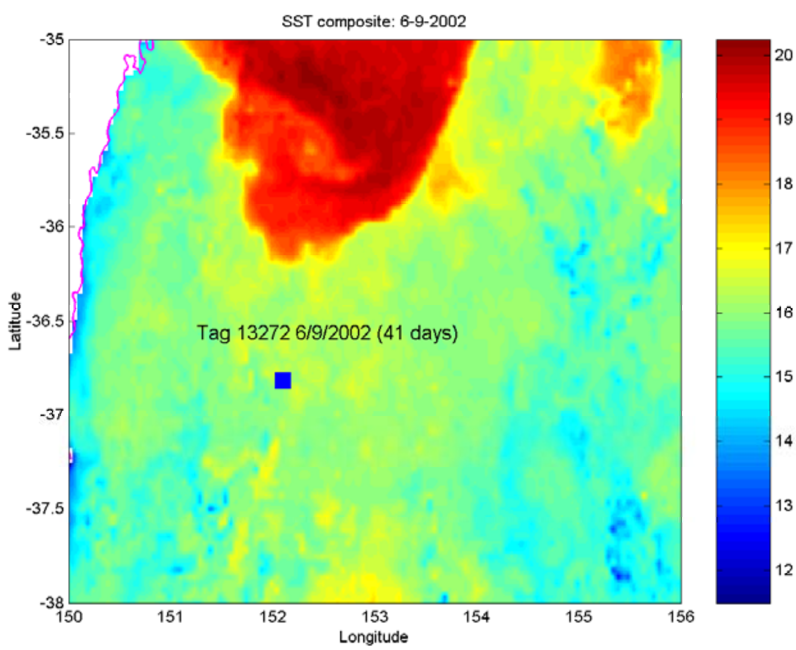


Figure 10. 3-day SST composites around popup locations. Tags are placed on composites according to whether they surfaced within three days of other tags. Note that cloud cover has distorted the SST signal for panels (c-e).



(a)



(b)

Figure 11. Pop-up positions for the 2002 releases. (a) Shows the pop-up position of SBT 28709 after 28 days, to be extremely close to the release position and in relatively similar water mass though the EAC is beginning to retreat northward. (b) Shows the pop-up position of SBT 13272 south of the retreating EAC. Note that image (b) is distorted by cloud cover.

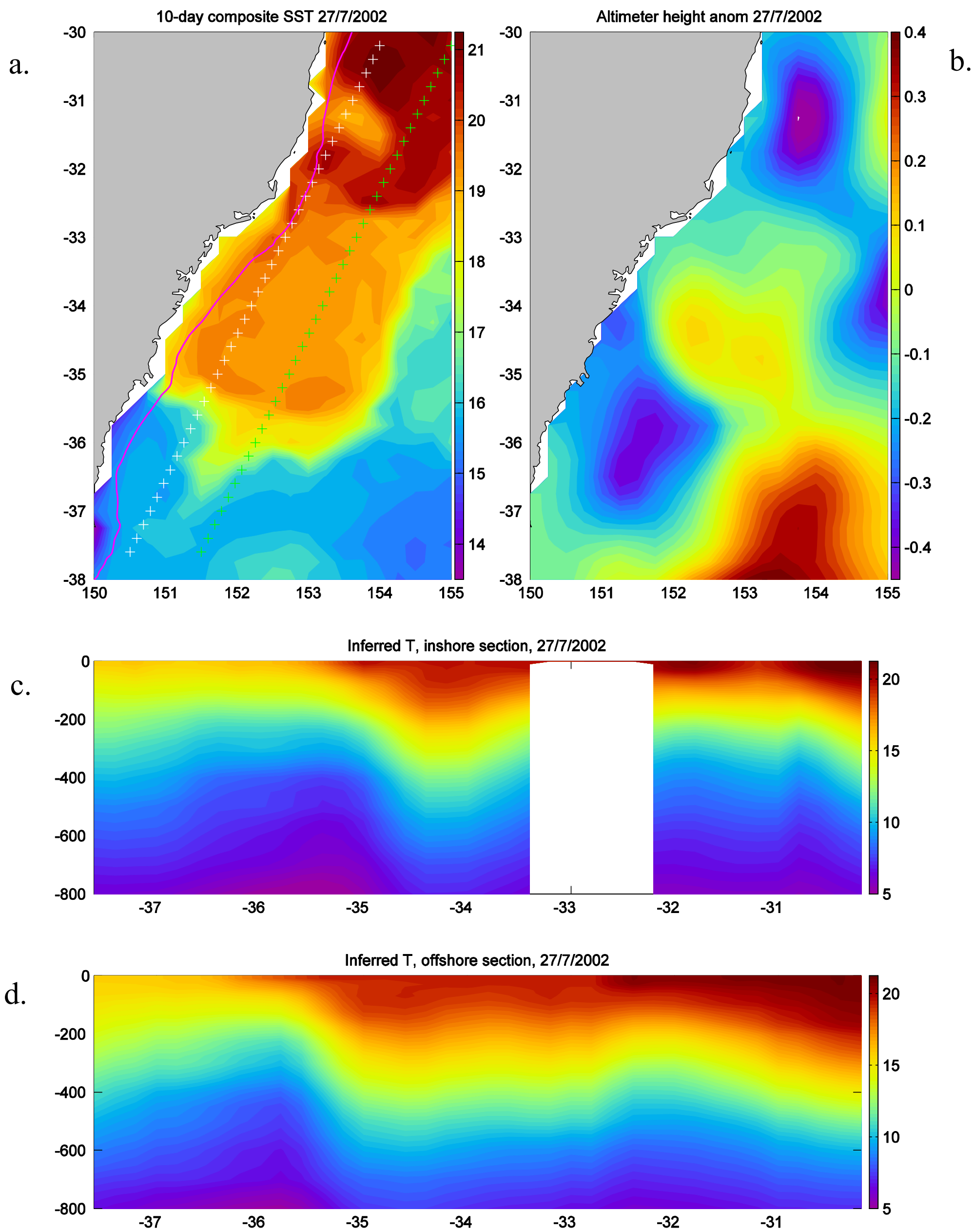


Figure 12. (a) 10-day SST composite centered on July 27, 2002. (b) Satellite altimetry data for the same period showing the extent of a large eddy (3 PATs were deployed on its southeastern edge). (c) Synthetic Bathythermograph from the CARS dataset for the inshore section shown in panel (a). (d) Synthetic Bathythermograph from the CARS dataset for the offshore section shown in panel (a). Panels (c-d) show that the 15-20^{o}C water, recorded by the PATS, extended to 200m on the frontal edge and to 400m in the eddy core.

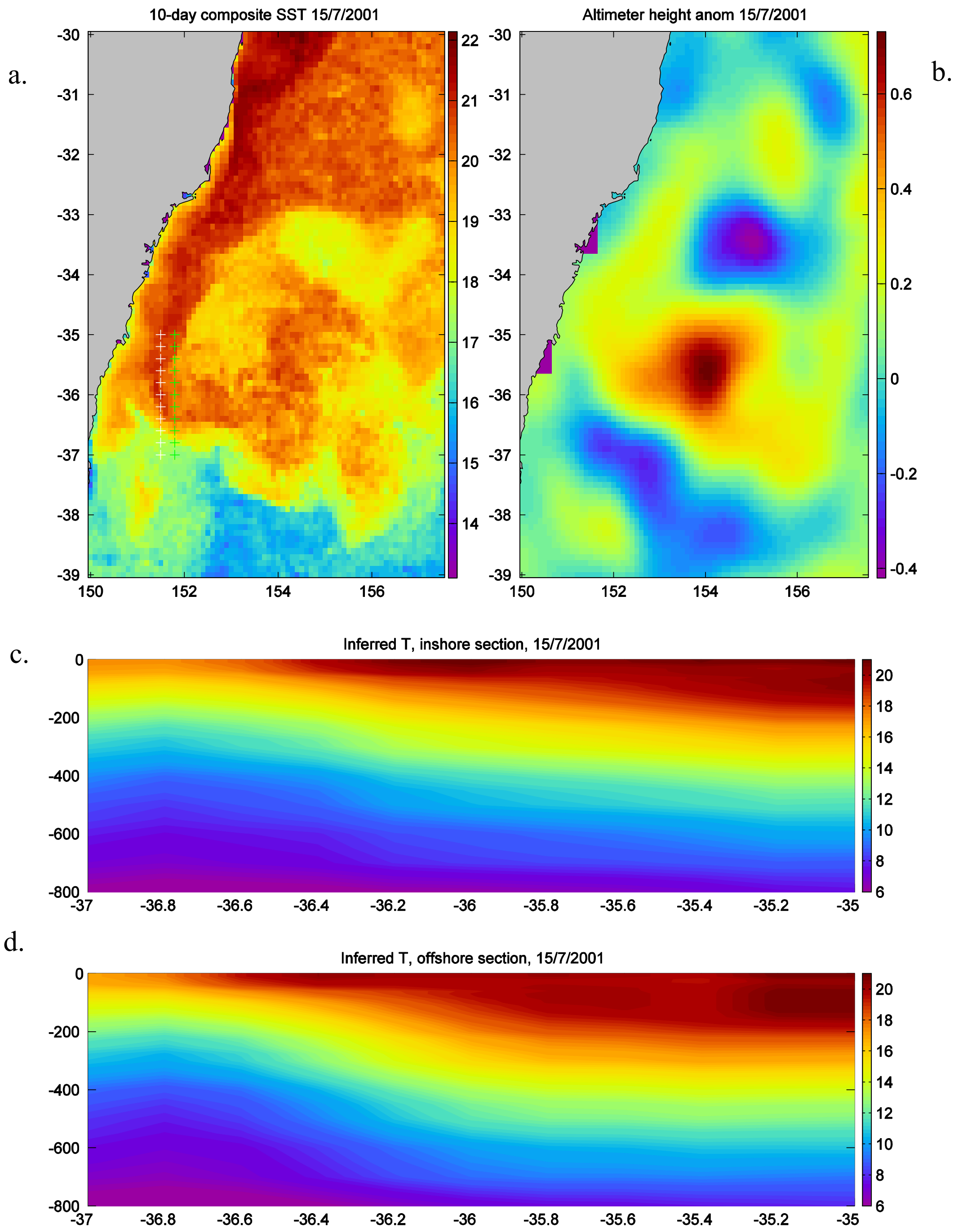


Figure 13. (a) 10-day SST composite and the location of the synthetic bathythermograph data shown in panels (c-d). (b) Altimetry data for 15-7-2001 showing the location of a prominent