

Understanding Apex Predator and Pelagic Fish Habitat Utilization in the California Current System by Integrating Animal Tracking with in situ Oceanographic Observations

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LONG-TERM GOALS

The team assembled includes researchers from the University of California Santa Cruz (UCSC), National Marine Fisheries Service (NMFS), and Stanford's Hopkins Marine Station. Researchers from these organizations will be responsible for orchestrating simultaneous multi-species tagging efforts. Oceanographers from the Environmental Research Division (ERD) at NMFS will provide expertise in remote sensing of the Northeast Pacific oceanography. The integration and analysis of the diverse datasets requires the development of new software which is being developed by the NMFS, UCSC, and Stanford as well as researchers from Sea Mammal Research Unit (SMRU) in Scotland. Using these software programs as well as others, we plan to map the oceanic habitats used by top predators in the California Current System (CCS). This will be done by examining both top down and bottom up processes, and predicting how climate variability impacts the distribution and utilization of oceanic habitats within the CCS. We are also developing methods that are required to integrate animal collected data into existing oceanographic databases.

OBJECTIVES

This study will develop a dynamic, ecosystem-based approach to map and understand habitat utilization by top predators in the CCS. Specifically, our objectives are:

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- (1) To map critical habitat of predators in the California Current System;
- (2) To link the movement patterns of these predators to physical and biological ocean features, in order to:
 - a. determine how ocean dynamics act to aggregate diverse organisms;
 - b. define the stability and community structure around biological hot spots;
 - c. define the persistence of hot spots in space and time;
 - d. examine the relationships among different species in the context of habitat utilization;
 - e. identify the influence of top down and bottom up processes and their influence on dynamics of hot spots;
- (3) To map habitat distribution of commercially-viable and threatened fish stocks in the CCS, based on predator distribution and behavior from tracking data;
- (4) To quantify the seasonal and interannual variability of mesoscale ocean features (potential hot spots) in the CCS, from remotely sensed and *in situ* data;
- (5) To contribute a significant quantity of high-resolution *in situ* oceanographic data from animal tags to coastal and global ocean observing programs;
- (6) To provide critical advice to fisheries managers on the distribution of commercially-viable fish stocks in relation to oceanographic variability;
- (7) To develop and test models that allow for the prediction of animal abundance and distribution based on the physical environment.

APPROACH AND WORK PLAN

Oceanographic data will be obtained from both satellite imagery and the electronic tags which record environmental variables such as temperature, depth, light and salinity. Physical data obtained by tagged animals will permit comparison to features that are spatially and temporally concurrent with the animals' foraging behavior. For example, temperature and salinity data collected by the tags will place the animals' behavior in the context of distinct water masses. Consequently, the animal-derived oceanographic data will be used to define water habitat types based on hierarchical agglomerative cluster analysis on temperature and salinity profiles. Another approach that has been fruitful in the Pacific Ocean is to define thermal discontinuities based on changes in bathythermographs recorded by the tags between animal dives. These thermal discontinuities are then examined in relation to the rates and patterns of movement and fine scale behavioral changes of the diving animal.

Large-scale habitat usage will be modeled based on individual animal utilization. Habitat preference is indicated when an animal uses an area more than would be expected based on relative habitat availability. This approach is complicated by impacts of serial autocorrelation on tracking data and by proximity of available areas to capture sites. Our approach to define habitat usage will be to start by modeling the relative accessibility of habitat mechanistically based on distance from a capture site, speed of movement, and the observed distribution of trip durations. These estimates will then be used as variables within a Generalized Additive Model (GAM) approach to relate the environmental variables that define habitats and spatial utilization by tagged animals.

One of the critical requirements in ecosystem-based resource management is learning how to define zones of high biological activity, or "biological hot spots". How best to characterize these "hot spots", whether determination is based on how animals use the habitat (behavioral changes), or how to quantify their temporal variability, stability and long-term viability, remains unknown. Regardless,

the first step is to identify where they occur. The Tagging Of Pacific Pelagics (TOPP) research program, which is composed of the member groups listed above, will provide new data on spatial and temporal characteristics of hot spots in the CCS as well as new methods to identify them using both remotely sensed oceanographic information and data obtained from the tagged animals.

The first step in identifying and characterizing hot spots is to better utilize the electronic tagging data. To do this, the team is drawing upon the best available computer code from both the marine mammal and tuna scientists involved in the collaborative program. For example, the Block lab (Stanford University) has been working closely with tag manufacturers (Lotek, Inc. and Wildlife Computers) to develop new approaches to analyze tag data from marine fishes. They have developed routines for providing a statistical measure of the robustness of location estimates for geolocating tags, algorithms for determining latitude from sea surface temperature, software for display of depth-temperature profiles from archival and pop-up satellite archival tags, and a code for estimating light extinction coefficients to determine the chlorophyll *a* maximum.

In the first phase of the NOPP grant, we will focus on automating routines that allow more rapid assessment of animal collected data and the habitat utilized by the tagged animals in relation to the surrounding oceanography. This will occur in two phases. Firstly, we will focus on delivery of tag derived data to a Live Access Server (LAS). This involves development of database code and data delivery in a seamless fashion from multiple archival tag sources, to ERD, NOAA. Secondly, data visualization software will be developed for both fish and marine mammal derived datasets. The fish research team intends to combine visualization and data analysis software developed from independent laboratories (e.g. Block lab) into one software package that can be integrated with ongoing TOPP funded efforts in the marine mammal area (Costa and Fedak labs). To accomplish this, the development of code specific to the complexities of diving fish, as well as air-breathing mammals, is required.

WORK COMPLETED

We are only in the initial phase of this grant as the award was not received until May 2005. Since this time we have hired two programmers one at UCSC (Robin Weber) and a second who will be based at Hopkins Marine Station. The partial salaries of two contract employees at NOAA ERD (Daniel Palacios and Petra Stegmann) are being supported by the NOAA component of this grant. Another scientific programmer will be recruited at ERD through these funds. We have also purchased several workstations and software for database management, programming, and data visualization. A data server that mirrors the server at Hopkins has also been ordered.

Data analyses are also beginning on several fronts. One of the more robust yet simpler datasets that is currently being analyzed is from our tracking studies on albatrosses. The albatrosses can sample vast areas of the oceans over relatively short time scales. Therefore, we are investigating which oceanographic features influence behavior and distribution of albatrosses in Hawaii. Because of the simplicity of the dataset (locations, activity, and SST measurements only) compared to other TOPP species, these analyses will provide a framework from which to develop more complicated analyses for the fish and mammal datasets. Part of these analyses relies on the development of codes for filtering and interpolating the tracking data. We now have codes and have validated the routines with data from

several species. The result of this analysis is in press in the Journal of Experimental Biology (Tremblay et al. 2006).

A second component of this effort is to develop mathematical approaches to determine where the animals are spending time foraging. In patchy environments, most animals forage exhibiting movement patterns consisting in area-restricted searching (ARS). To this end we have compared the satellite tracks of 7 albatross and 7 northern elephant seals using transit speed (slow transit = area of increased search or feeding), angularity (areas of high rate of change in bearing), first passage time (time to cover areas of radius with high variance) and an index of fractal dimension. These indices were then compared to a more accepted index of foraging behavior that of the 2 D shape of the time depth record. A paper describing this analysis is under review in Deep Sea Research II (Robinson et al.).

Finally, we have developed a new method: the fractal landscape analysis. By moving a segment of a given distance along the track, and measuring fractal dimension of each segment, we described peaks and valleys of fractal dimension against time. Peaks from this fractal landscape correspond to the ARS zones and permits to individually pinpoint them. A publication describing this approach has been submitted to the Proceedings of the Royal Society (Tremblay et al.)

An additional dataset that we are working with to is that collected for bluefin tuna. Following the recovery of over 100 archival tags, we now have over 35,000 days of data on movements and behaviors in the California Current and across the Pacific. In conjunction with efforts ongoing in the TOPP program we are developing software that allow us to extract basic information on movements and behaviors, integrate tag and oceanographic data from external sources, and use the tag data to recreate the environment along the track using both the temperature and light data (Figure 1). From light data it is possible to measure relative changes in chlorophyll *a* concentrations. Comparing behaviors to information obtained on vertical water column structure from the tags is critical to understanding habitat use both inside and outside of hotspots. In addition to recreating the water column along the track we have spent considerable effort identifying the geographic location of hotspots over a range of temporal scales, efforts to link these locations to regional features is ongoing.

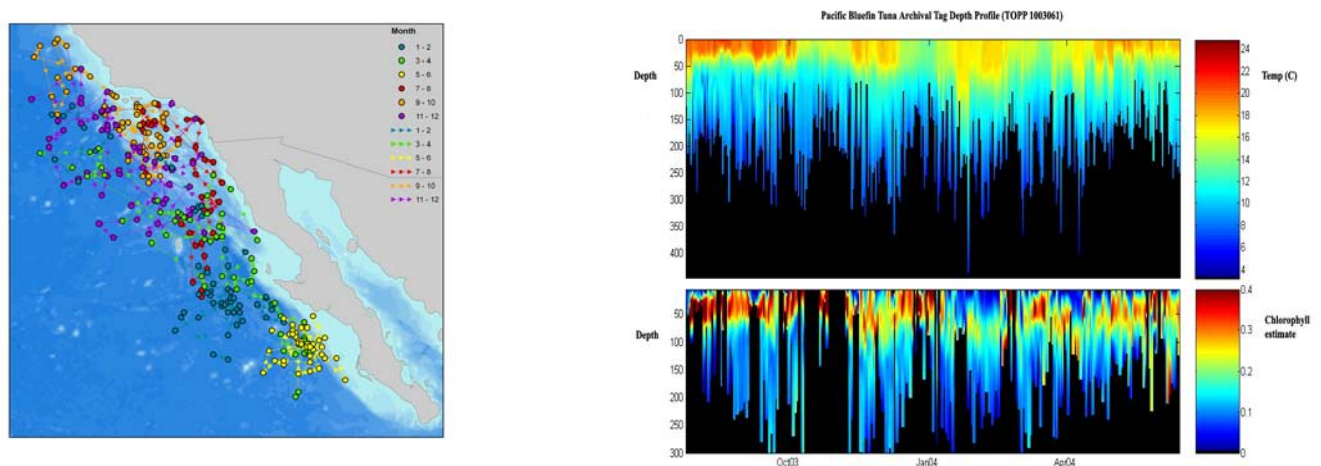


Figure 1. Shown for the track of bluefin 1441 are the geographic locations (left) determined using light-based longitude and SST-based latitude and the corresponding water column

temperature profile (right top) and estimates of the chlorophyll a concentrations (right bottom) over the course of the track.

Another early phase of this NOPP-funded research is to compare the hot spots identified independently from the tagged animals and from in situ and satellite-derived oceanographic data. We have used remote sensing observations from multiple satellite platforms to identify and characterize physical features in selected regions of the North Pacific that might constitute biological hot spots (Palacios et al., 2005). We classify these hot spots based on their spatial scale, degree of persistence or intermittence, forcing mechanism, and potential biological impacts. Satellite oceanographic monitoring, combined with data from large-scale electronic tagging experiments, can be used to conduct a census of biological hot spots, to understand behavioral changes and species interactions within hot spots, and to differentiate the preferred pelagic habitats of different species. Figure 2 shows examples of a variety of oceanographic features in different oceanographic environments that are heavily utilized by TOPP animals. Results from this analysis will be compared to the analyses of habitat usage from the TOPP animals.

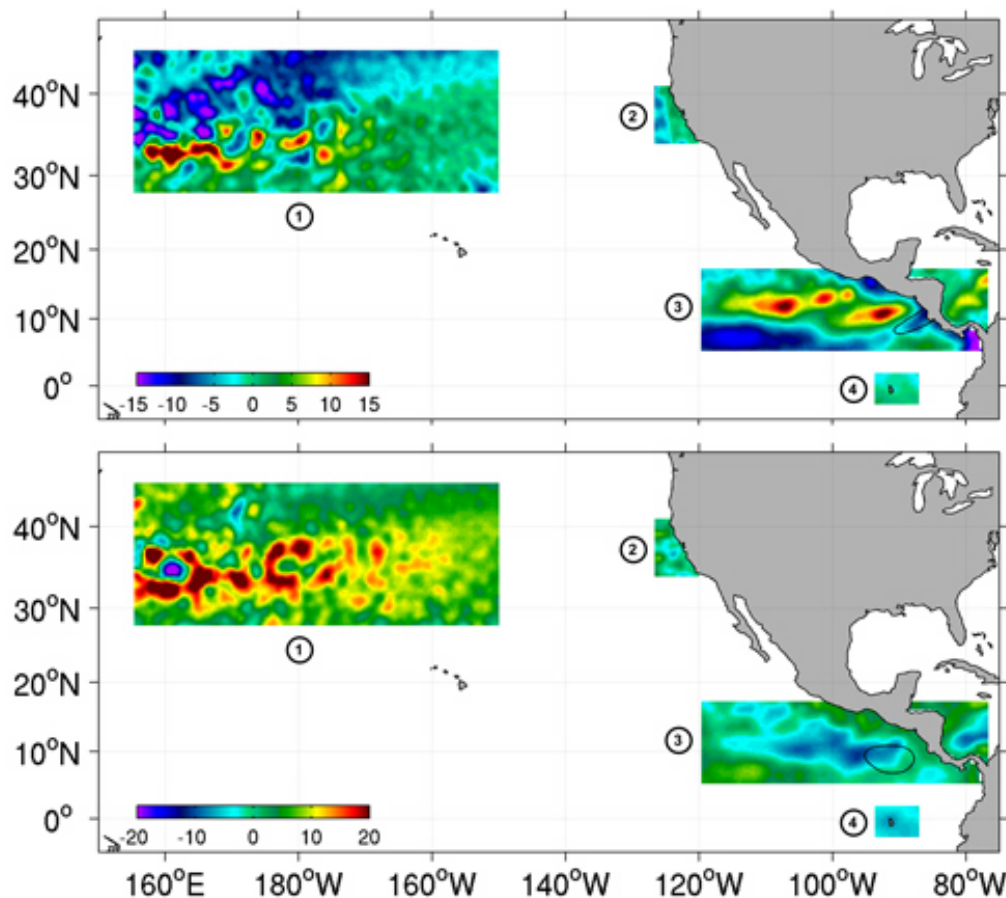


Figure 2. Mean sea level anomaly (in cm) for February (top) and August (bottom) for four regions in the North Pacific. (1) Central North Pacific, (2) central California Current System, (3) northeastern tropical Pacific, and (4) Galápagos Islands. Seasonally persistent oceanographic features can be identified in each region.

In addition to this large-scale study, a more detailed study of oceanographic hot spots in the northeastern tropical Pacific has been completed (Palacios and Bograd, 2005). We used a 12-year time series of satellite altimetry to characterize long-lived, wind-generated anticyclonic eddies originating in the Gulfs of Tehuantepec and Papagayo, a region frequented by leatherback sea turtles and other top predators (Figure 3). These eddies are important transporters of nutrient-rich coastal waters and biogenic material from the continental margin to the interior northeastern tropical Pacific. Their annual recurrence, intensity, and persistence suggest that they may be critical biological hot spots. We observed strong variability in eddy activity, with a greater number of eddies, more intense eddies, and a longer eddy season during El Niño years. A similar analysis is currently underway for the California Current System, the region encompassing the majority of TOPP data.

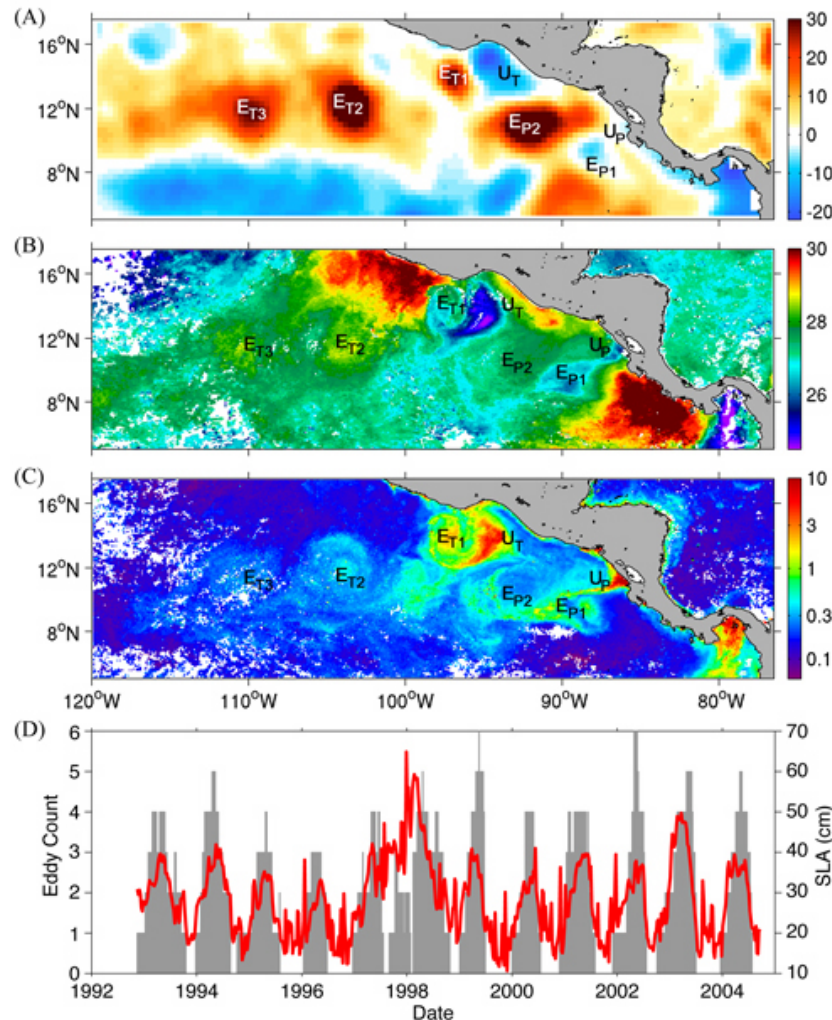


Figure 3. (a) Sea level anomaly (in cm) for the 7-day period 30 January - 5 February 2003, (b) SST ($^{\circ}\text{C}$), and (c) chlorophyll (in mg m^{-3}) for the 8-day period 2-9 February 2003. (d) Frequency histogram of number (gray) and peak intensity (red) of all eddies observed in the region between October 1992 and August 2004.

Drs. Costa and Fedak (of SMRU) have also organized a symposium at the upcoming Oceans 2006 conference in Hawaii, February 2006. The conference symposium is entitled “New Platforms for Operational Oceanography: Enlisting Marine Top Predators to Describe Their Environment “ and will

focus on studies using animals as ocean sensors. A total of 21 abstracts were received for the symposium. Fourteen of these are oral presentations in session OS13D and OS14D on Monday February 20 2006 and nine will be given as posters in session OS15G.

RESULTS

Preliminary analyses of our investigations with the albatross datasets show distinct behavioral differences between the two sympatrically breeding species being studied. For example, Laysan albatrosses travel much further while at sea and they exhibit a strong tendency to fly farther north in west to east movements along the North Pacific current and Transition Zone Chlorophyll Front. Black-footed albatrosses fly to areas further south and within a smaller area. We have also compared specific foraging behaviors to certain oceanographic features. For example, some albatrosses appear to associate with sea surface height anomaly gradients (Figure 4). More in depth analyses are forthcoming.

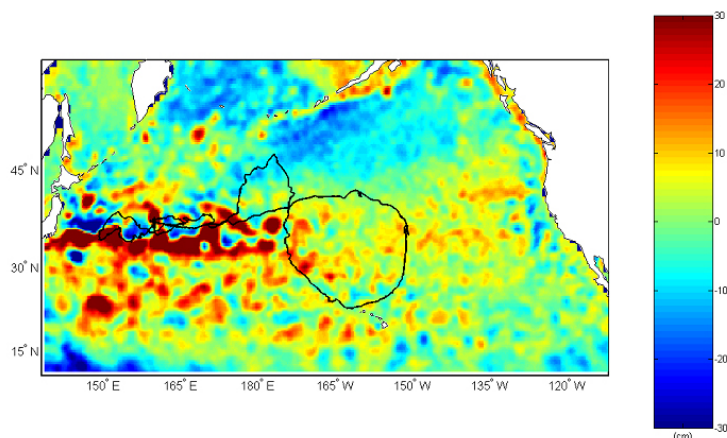


Figure 4. The satellite track of a Laysan albatrosses originating in Hawaii covering 28 days and over 20,000 km. The track is overlaid on remotely sensed Sea Surface Height (SSH). Movement patterns suggests this bird was tracking SSH anomalies along the North Pacific Current.

For the bluefin tuna dataset, we have identified a number of hotspots in the East and West Pacific. The vast majority of tags have been recovered in the eastern Pacific providing a large data set with which to examine seasonal patterns in the California Current (Figure 5). Bluefin are most commonly found off central Baja California in the winter and move to southern Baja in the spring. In the summer, these fish move north to the waters off northern Baja and the Southern California Bight. They continue north in the fall, moving past Point Conception to the waters off central and northern California. This northward movement is likely timed with the increasing productivity in these coastal waters at this time of year. Efforts to quantify the links between productivity and movement patterns are underway.

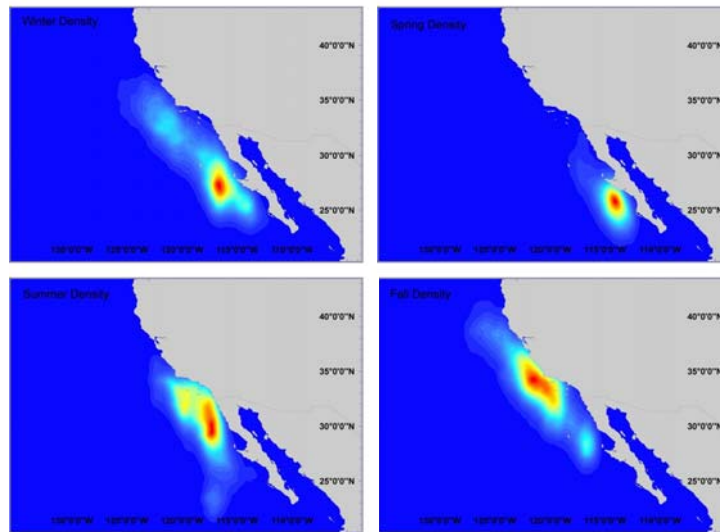


Figure 5. Kernel density maps showing the seasonal distribution of bluefin tuna tagged in 2002 and 2003.

While most tags have been recovered in the east, seven tuna have been recaptured near Japan after making trans-Pacific migrations. Interestingly the path and timing of their eastern migration among all fish is similar (Figure 6). Movement east to west was initiated in the winter and spring with bluefin tuna making this voyage along the northern transition zone at latitudes between 30 and 38° N. Another characteristic that is consistent among individuals is the increased residence time in the western Pacific between 180 and 150° E during the spring. This area may be an important foraging ground and efforts are underway to characterize this region including the overlap with other TOPP species such as the albatross, which also frequent this area (Figure 4). Analysis of these datasets by Perle and Polovina (In preparation) will detail the influence of oceanography on movements.

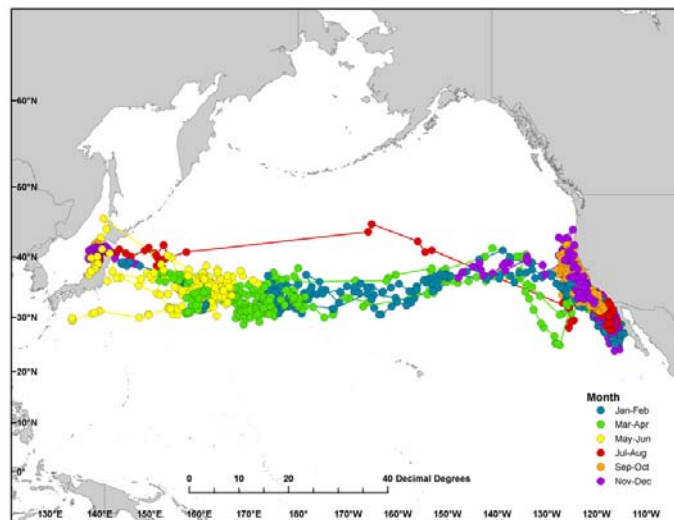
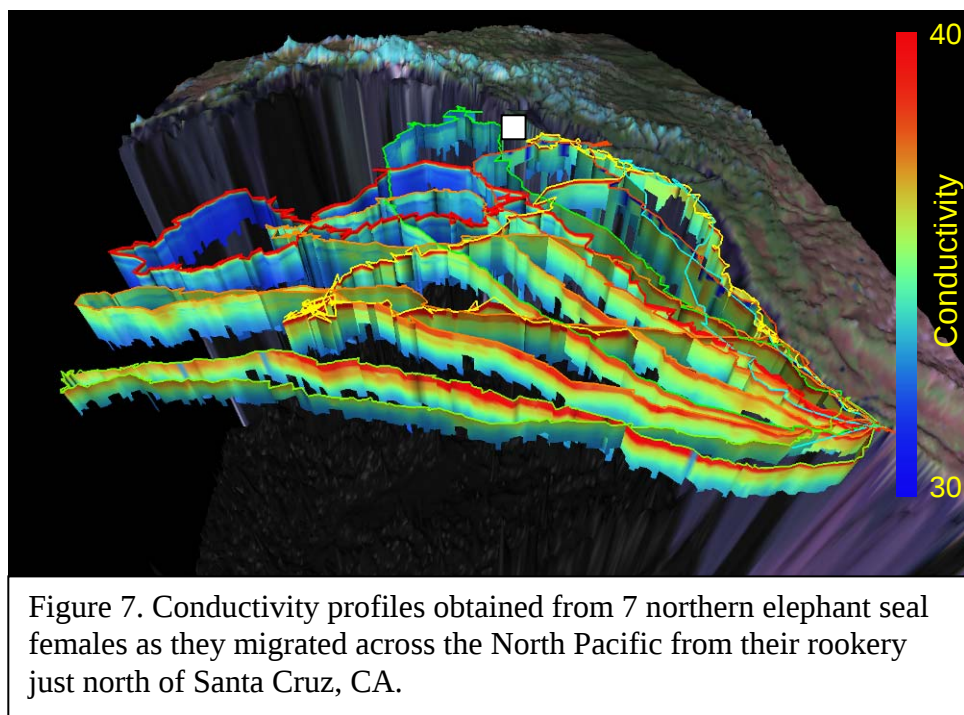


Figure 6. Trans-Pacific movements of four bluefin tuna showing the consistency in both the path and timing of movement across the Pacific. The red line to the north is for the one animal that returned to the east prior to making a second trip west in the subsequent year.

Using the fractal landscape analysis we compared ARS behavior of Laysan albatrosses (*Phoebastria immutabilis*) and northern elephant seals (*Mirounga angustirostris*), two very distinct North Pacific top-predators. ARS zones of albatrosses and seals were extremely similar in size, despite large differences in motility between the 2 species. This suggests that ARS zones are primarily determined by exogenous factors, such as oceanographic condition and prey distribution, rather than by predators' ability to travel. In addition, the timing of ARS zones was concentrated during sunrise and sunset in albatrosses, but not in seals. Seals and albatrosses spent respectively about 5 and 0.5 days in each zone. This suggests that the relative availability and persistency of prey fields to the predators differed. The diel vertical migration of the major prey of these predators, relative to the difference in their diving ability is proposed as a possible factor for shaping the timing of ARS behavior. We conclude that spatial descriptors of ARS zones are mostly environment dependant, whereas temporal descriptors are mostly predator dependant.

The CTD (Conductivity, temperature and depth) tags developed under our previous NOPP award are now being routinely deployed on elephant seals and California sea lions to obtain temperature and salinity profiles across the North Pacific Ocean (Figure 7).



IMPACT/APPLICATIONS

Our ability to identify oceanic hotspots used by marine predators will have significant implications for fisheries management and conservation. For example, areas that are deemed “sensitive” or critical to the proliferation of a given species could be protected or managed. However, because the oceans are

so dynamic, it is important to identify key features or consistent phenomena (e.g. coastal upwelling or other physical forcing) that affect ocean productivity and the aggregation of predators and prey.

TRANSITIONS

Economic Development

The GPS tag design developed by WildTrack Ltd (Leeds England) with support from our previous NOPP award is now under production by the Sea Mammal Research Unit and has been licensed to Wildlife Computers Inc (Redmond WA). As part of the current NOPP effort we have been involved the first test deployments of these tags. These tags are expected to be come commercially available by February 2006.

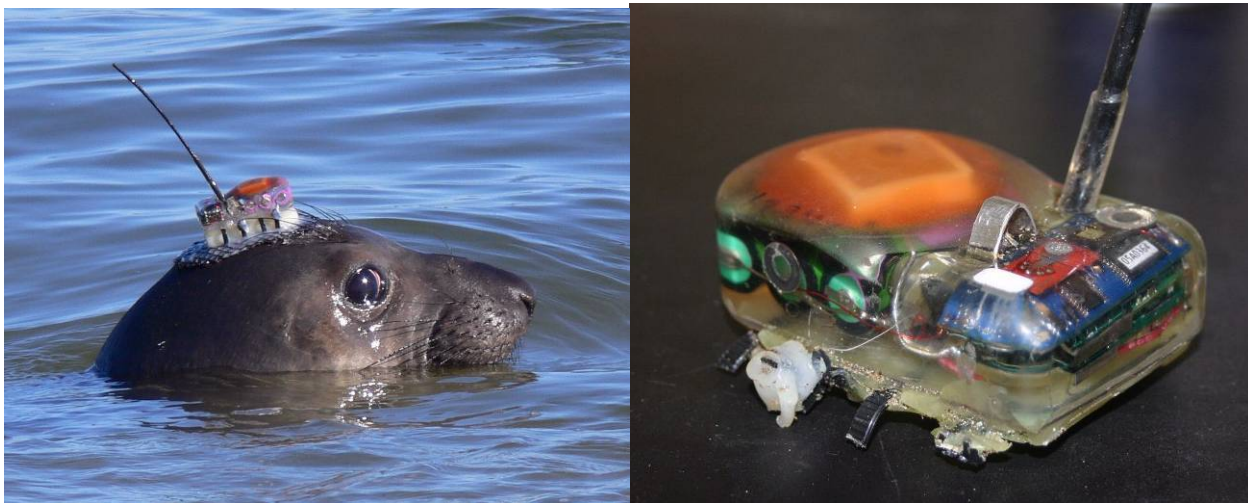


Figure 8. Left a 2 year old northern elephant seal at sea wearing the newly developed Wildlife Computer GPS. Right. Close up image of the GPS tag after recovery.

Science Education and Communication

The NOPP award has directly supported 2 post doctoral researchers and 2 graduate students. The results of this research are communicated to the public on the TOPP web page, www.toppcensus.org.

RELATED PROJECTS

This project is closely linked to the Tagging of Pacific Pelagics program (TOPP) which is a pilot project of the Census of Marine Life (<http://www.toppcensus.org>). All the electronic tagging data for the project will be obtained from animals deployed as a part of the TOPP program. TOPP is pioneering the application of biologging science to study pelagic habitat use by marine vertebrates and large squid in the North Pacific. The program has four primary long-term goals. First, develop methods and equipment necessary to implement large-scale, multi-institutional, multi-species electronic tagging programs. Second, improve basic knowledge of oceans, species and key processes linking apex predators to their ocean environs. Third, integrate environmental data collected by the tagged animals into global oceanographic databases for use in ocean observation, model testing and

development. Fourth, build an education and outreach program that will educate the public about the marine environment and associated conservation issues.

PUBLICATIONS

Palacios, D.M., Bograd, S.J., Foley, D.G., and Schwing, F.B., 2005. Characteristics of oceanographic hot spots in the North Pacific. *Deep-Sea Res. II*, in press.

Palacios, D.M., and Bograd, S.J., 2005. A census of Tehuantepec and Papagayo eddies in the northeastern tropical Pacific. *Geophys. Res. Lett.*, in press.

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