

Final Report

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Project Title: Behavioral, Dietary, And Demographic Responses Of Hawaiian Albatrosses To Environmental Change

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Signature of Submitting Official:

A handwritten signature in black ink, appearing to read "Scott A. Shaffer". The signature is fluid and cursive, with the first name "Scott" and last name "Shaffer" clearly distinguishable.

2. PUBLIC SUMMARY: Pelagic seabirds (albatrosses and petrels) find food by relying on distinct oceanographic features like transition zones, upwelling, and large eddies. These oceanographic features change intensity, distribution, and duration during El Niño/La Niña events resulting in poor breeding performance in seabirds. Climate models predict that these perturbations will last longer, be more variable, and in some cases, cause major shifts in oceanographic regimes. We analyzed our decade-long dataset of tracked Laysan and black-footed albatrosses (N = 192 individual trips) the breed in the Northwest Hawaiian Islands to investigate the mechanistic role that oceanography plays in affecting the foraging distributions and its subsequent feedback on breeding performance in albatrosses. We compared the total distance traveled, maximum foraging range, trip duration, and the distribution of albatrosses in each year to the distance of the Transition Zone Chlorophyll Front (TZCF) and found that albatrosses traveled farther and for significantly longer durations when the TZCF was greater than 700 km from the colony. The distance of the TZCF to the breeding site was influenced by several climatological features like the Pacific Decadal Oscillation, Multivariate ENSO Index, Northern Oscillation Index, and the North Pacific Gyre Oscillation index. A modeled composite of these features explained a significant amount of variation in the trend of breeding performance in Laysan albatrosses over the last 30 years. No such pattern was observed for black-footed albatrosses. Stomach oil collected from 96 breeding albatrosses was analyzed for fatty acid signatures to examine interannual differences (2010-2012) in the diets of both species. No interannual differences were observed but a complete characterization of albatross diet was obtained. Overall, the results from this project highlight possible mechanisms (i.e. features of the ocean) that explain variation in breeding performance. From this, connections can be made about long-term population viability to possible climate change scenarios.

3. PROJECT REPORT

A. TECHNICAL SUMMARY: For marine apex predators, understanding the factors that regulate or influence population dynamics is essential for developing predictive models about climate change impacts. With financial assistance from PICCC, we were able to mine our existing time series of tracking data for Laysan and black-footed albatrosses and compare it to specific oceanographic features and test whether key behavioral indices (e.g. travel distance, time at sea, maximum range) varied with the intensity, duration, and spatial extent of the oceanographic features in the North Pacific. Furthermore, we modeled the impacts that these oceanographic features had on reproductive success as a corollary to understanding the influence on behavior. Finally, we analyzed the diets of both albatross species to understand the variation across years and between species. Overall, our analysis showed that the proximity of Transition Zone Chlorophyll Front (TZCF), a major productivity gradient that spans the North Pacific, to the breeding colony increases the duration, maximum range, and total distance of albatross foraging trips. These factors combined with ocean climatologies (e.g. PDO, NEI, etc) explained a significant amount of variation in breeding success of the albatrosses. This outcome is powerful because we now have a more solid mechanistic linkage between environmental influence and population regulation of marine apex predators in the North Pacific with which to model future changes in ocean climate. In addition, we characterized albatross diets from stomach oil using fatty acid signature

analysis. Although we did not have enough interannual variation in our samples, these data could be used to monitor future changes in specific prey species. Thus, we view this analysis as an addition to the limited data on albatross diets in the North Pacific and they provide a valuable baseline that can be compared to future samples. In summary, the outputs of our analyses can be used to facilitate future modeling efforts by providing greater direction on input parameters.

- B. PURPOSE AND OBJECTIVES:** The purpose of our study was to understand the mechanisms or linkages between albatross foraging ecology, breeding success, and large scale environmental perturbations. The objectives were to 1) mine our existing time series datasets with the specific purpose of identifying the variation in behavior and distribution during a normal and anomalous years, like the El Niño/La Niña cycle that is currently predicted; 2) examine interannual variations in diet based upon Fatty Acid Signature analysis; 3) compare the variations in behavior, distribution, and diet during 'normal' versus anomalous years; 4) evaluate the response in breeding success/failure associated with behavior, distribution, and diet across years; and 5) and create or assist development efforts of a model that can be used to predict future changes in the aforementioned parameters based on variable climate scenarios. Overall, completion of these objectives will provide resource managers with critical information for strategic planning in Conservation Management and climate modeling.

We completed the analysis for objectives 1 through 4. The results of objectives 1, 3, and 4 are presented in a manuscript entitled 'Fronts, Food, and Fitness: Linking Environment to Reproduction in Two North Pacific Albatross Species' by Thorne et al. The results of objective 2 are part of a doctoral dissertation and will ultimately appear as part of a peer-reviewed manuscript in spring 2015. It is possible that objective 5 will be further explored in a future paper but this is unclear at the moment because a key member of our team (Dave Foley) died in December 2013. Nevertheless, we are happy to provide data or assist further development of any large scale modeling effort that PICCC pursues.

C. ORGANIZATION AND APPROACH:

Quality control of data – All metadata for each albatross individual studied was checked against field notebooks. This included banding data, tag deployment and recovery dates and times, tag type and number, breeding status, and sex if known. All tracking data were quality controlled to check for errors in assignment to individual birds, completeness of a track, and erroneous locations within a track. All anomalies were corrected or removed. USFWS staff provided data for reproductive success at Tern Island. They conducted their own quality control analysis and provided the data as percentage of chicks hatched per eggs laid for each year of our study (Figure 1).

Analysis of behavioral data and oceanographic habitat - We examined albatross movements during the incubation and brooding periods from 2002-2010 using satellite tracking tags and GPS loggers. A total of 100 trips for Laysan albatrosses and 92 trips for black-footed albatrosses were examined during this time period. We assessed

cumulative trip distance during each albatross foraging trip, maximum distance from Tern Island, and maximum and minimum values of latitude and longitude during each trip. To examine albatross movement in relation to the location of the TZCF, we extracted distances to TZCF for each track position using daily rasters of TZCF location then calculated the proportion of each track spent north of the TZCF. The TZCF is a basin-wide front, spanning more than 8000 km across the North Pacific, representing a zone of convergence. It is defined by a sharp chlorophyll gradient, which can be represented by a chlorophyll density of 0.2 mg/m^3 and 18°C isotherm in SST (Bograd et al. 2004). This allowed us to localize the front on a daily time scale using daily Group for High Resolution SST (GRHSST) images with a 5 km resolution. We estimated that a distance of 700 km (i.e., a 1400 km round-trip distance) would be easily attainable by both Laysan and black-footed albatrosses based average trip distances during the brooding period (the most constrained period). We then assessed the number of days each winter (January through March) that the TZCF was within 700 km of Tern Island (*sensu* Figure 2) and included this metric within our analyses of oceanographic variability relative to variability in albatross reproductive success. All spatial analyses were conducted in ArcGIS 10.0 using the spatial analyst extension.

Analysis of climatological data and modeling – Indices of large-scale oceanographic processes represent climatic and oceanographic variability in the central North Pacific: Pacific Decadal Oscillation (PDO), Multivariate ENSO Index (MEI), Northern Oscillation Index (NOI), and the North Pacific Gyre Oscillation index (NPGO). PDO reflects a low-frequency pattern of Pacific climatic variability representing changes in SST in the North Pacific (Mantua et al. 1997). MEI identifies ENSO events using variability in six variables over the tropical Pacific (Wolter and Timlin 1998). Positive values of MEI represent El Niño conditions, while negative values represent La Niña conditions. NOI is a broad index of climatic variability that represents the difference in sea level pressure between the North Pacific High and the low pressure system centered over Darwin, Australia (Schwing et al. 2002). In order to examine the effects of climatic indices on albatross breeding success, we examined average, minimum and maximum values of PDO, MEI, NOI and NPGO both on an annual scale and exclusively during the winter breeding months (December to March).

Principle Components Analysis (PCA) and Generalized Linear Models (GLMs) were used to examine the effects of multiple climatic indices on albatross trip metrics and reproductive success. PCA provides a means of summarizing the variability in a number of different correlated variables into fewer independent, orthogonal axes and allowed us to represent variability in the following climatic and oceanographic predictors: PDO, MEI, NPGO, NOI, and proximity of the TZCF. We constructed separate PCAs to summarize environmental variation and to evaluate the effects of this environmental variation on albatross biology at two scales: at an annual level to evaluate the reproductive success (Figure 1) of Laysan and black-footed albatrosses; and at the trip level to assess effects on albatross trip metrics (Figures 2-4).

Analysis of diet from fatty acid signatures - Quantitative fatty acid analysis (QFASA) was successfully run on 106 albatross stomach oil samples (Laysan, N = 53 ; black-footed, N = 53) collected from 96 adults and 10 chicks across the incubation and chick-brood stages from years 2010, 2011 (*incubation only*), and 2012 at Tern Island. Thirty-five species of potential albatross prey, representing 13 functional groups, and sourced from the North Pacific Transition Zone, Hawaiian waters, the California Current, and a bait supplier for the Hawaiian long-line fleet, were included in the prey library required for the QFASA model. We used a novel method for lipid analysis by isolating triacylglycerol (TAG) lipid classes from waxy ester (WE) lipid classes and incorporated both in our analysis, since many marine organisms exhibit a relatively large amount of WE in storage tissues. Our results from QFASA are realistic to prior expectations and can be validated from previous diet studies on Laysan and black-footed albatross. The strength of our model likely comes from: 1) our extensive prey library, sourced from across the range of North Pacific albatrosses, 2) the additional component of the WE lipid class, and 3) no need for a calibration coefficient since albatross oil is derived directly from prey and does not undergo metabolic transformation before sampling.

D. PROJECT RESULTS:

Analysis of behavioral data and oceanographic habitat - The models generally performed well, explaining 23-70% of the variability in trip metrics for Laysan albatross trips and 30-74% of the variability in black-footed albatross trip metrics. Laysan albatrosses traveled farther from the nest during the incubating stage and trips were longer when the TZCF was more than 700 km from Tern Island (Figure 3). These patterns indicate that when both incubating and brooding tracks were considered together, albatrosses travelled farther when the TZCF was farther away, but there was no apparent trend in distance traveled during the brooding phase relative to the location of the TZCF. In addition, the total trip distance was higher when North Pacific gyre conditions (PC 2) were strong. Similar trends in Laysan albatross trips were observed in trip duration, which showed a strong negative relationship with distance to TZCF from Tern Island (PC 3). The latitude range was lower during the brooding phase, and a weakly significant interaction between the location of the TZCF and the breeding status of the birds indicated lower latitude ranges during the brooding phase. A lower proportion of trips were spent north of the front during the brooding phase in comparison to the incubating phase.

The best model for black-footed albatrosses, describing variability in trip distance included only breeding status, again highlighting that brooding trips are significantly shorter than incubating trips. The model describing the farthest distance traveled from Tern Island reflected shorter distances travelled during the brooding stage, but also included a weakly significant interaction between distance of the TZCF from Tern Island (PC 3) and breeding stage. The model examining the proportion of time spent north of the TZCF indicated that black-footed albatrosses spent more time north of the TZCF during weak gyre conditions and when the TZCF was far from Tern Island.

Analysis of climatological data and modeling – At an annual level, the first three PC axes represented 89% of the variation in the data. The GLM assessing how PC axes influenced reproductive success performed relatively well for Laysan albatrosses, explaining 39% of the variability in reproductive success across the 31-year time series. The final model included only the first PC axis, and indicated that Laysan Albatross reproductive success was negatively correlated with minimum distance to TZCF and MEI, and positively correlated with NPGO, PDO and NOI. While the GLM for black-footed albatross reproductive success showed similar relationships, the model explained only 9% of the variation in reproductive success. Four years (1984, 1999, 2008 and 2012) showed particularly marked declines in reproductive success for both species (Figure 1), and three of these years (1999, 2008 and 2012) represented the three highest loadings along PC axis 1.

Analysis of diet from fatty acid signatures - Preliminary QFASA results indicate wide population niche-breadths in both species, showing the utilization of prey from almost all functional groups of prey (Figure 5). Although, our results reinforce the classification of North Pacific albatross species as generalist foragers, it is highly notable that there appears to be a large component of individual dietary specialization present in both species. Significant differences in the diet composition between species exist, mainly driven by pelagic decapods, flying fish roe, swordfish being a much larger component in black-footed albatross diet, while Laysan albatross exploit to a greater extent both large (adult *Gonatus borealis*) and small (*Gonatus berryi*, *Berryteuthis anonychous*) vertically-migrating muscular squid. Black-footed albatrosses show a significant difference in diet composition between the incubation and chick-brood periods, while Laysan albatrosses do not. Black-footed albatrosses utilize more decapod shrimp and flying fish roe in the brooding period, whereas the incubation period was characterized by larger amounts of mesopelagic gelatinous and vertically migrating squid. Though there was no significant difference in diet composition for Laysan albatrosses between incubation and chick-brood, the large vertically migrating squid *G. borealis*, abundant in NPTZ waters, stood out as being more influential in incubation diet.

Breeding year (i.e. 2010 vs. 2011) nor breeding year/phase (i.e. Incubation 2010 vs. Incubation 2011) did not drive any differences in diet composition for either species of albatross, indicating that North Pacific albatross species likely change their foraging patterns relative to ocean conditions (and subsequently prey), rather than maintaining a static movement pattern between years, which is also reinforced by patterns seen in our tracking efforts.

One of our most exciting results is that there is a large amount of individual specialization in these two albatross species, even though they are considered generalist species and, as a population, consume a wide array of resources. To assess dietary specialization in individuals within a population, a longitudinal sampling design of dietary collection is required. Since albatross stomach oil integrates diet consumed over a long timescale (multiple weeks), it represents multiple foraging events/decisions and therefore can be classified as a longitudinal diet sample. We used Roughgarden's 1972 measure of the amount of individual specialization within a population: Within-

Individual Component divided by the Total Niche Width Component (WIC/TNW). Then we calculated a proportional similarity index for each individual (PSi) to calculate individual measures of niche breadth in comparison to population niche breadth. Overall, there was significant niche specialization between both species, among age classes, and between breeding stages (Figure 6).

E. KEY FINDINGS: There were a number of key findings from this research project that are outlined below.

- 1) **Establishing a mechanistic link between albatross reproductive success and oceanography of the North Pacific.** By combining a number of oceanographic indices or climatologies, we were able to explain a significant proportion of the variation in breeding success of albatrosses related to large-scale climate events like ENSO (Figure 7). This is an important discovery because although several studies have purported to show or really infer that these events influences on breeding success, we were able to successfully show this affect at the population level for an apex marine predator in the North Pacific. The importance to long-term modeling of climate change is critical as models are only as good as the data feeding the model and the best models have the fewest number of variables. What is needed now are comparisons of these models to the breeding success of other closely related species to test their generality. The establishment of a mechanistic link is key.
- 2) **Documenting and establishing links between albatross foraging behavior and a prominent oceanographic feature of the North Pacific.** We were able to establish proximate links between foraging behavior and the variation in proximity of a large-scale oceanographic feature. Although perhaps not as novel because other studies have documented similar relationships (albeit in a variety of systems), few studies in the marine environment have documented environmental affects on specific foraging behavior in marine predators. Albatrosses are especially challenging because they range so widely over the open sea that a number of features can integrate to form a combined effect. We were able to show that a prominent large scale feature like the TZCF is an important habitat for North Pacific albatrosses and this feature/habitat is predicted to move farther north as a result of climate change (Hazen et al. 2012). Indeed, we show that this habitat has been moving farther north over the last 30 years (Figure 8). Tern Island represents a relatively small fraction of the total albatross population in the Northwest Hawaiian Islands. Therefore, it is not clear how other populations that are further north (e.g. Laysan Island and Midway Atoll) will respond to the TZCF moving farther north. However, our finding does have relevance to albatross populations that breed in the main Hawaiian Islands (e.g. Kauai, Oahu, Lehua). The populations in the main Hawaiian Islands may be saved by breeding at higher elevations but they may be required to forage in habitat less favorable than populations that can access the TZCF. We would recommend additional longitudinal studies on the current populations in the main Hawaiian Islands to understand whether they use the TZCF or some other feature. It would seem unlikely during the most constraining period (i.e. chick brooding) so where the albatrosses forage has relevance to what occurs in the

Northwest Hawaiian Islands. There are colonies on islands in Mexico (e.g. Guadalupe Island) so its clear that albatrosses can breed along the eastern North Pacific. Perhaps some thought should be given to establishing colonies in the Channel Islands off California. These island are similar in habitat to Mexico, the elevation is good, and the California Current is already a productive location that albatrosses from Hawaii and Mexico already visit.

- 3) **Establishing the utility of fatty acid signatures analysis to quantify albatross diets from stomach oil collected in the field.** The importance of this result confirms what has been shown based on the analysis of wet diets; that albatrosses are typically generalist predators. However, we also show that there is some specialization among individuals within a species but across age classes, which has not been established for North Pacific albatrosses based on wet diets. The entire sample collection involved a 10 mL aliquot of stomach oil, which was easily collected in the field with an intubation tube in a procedure that can take less than a minute to perform. Thus, the simplicity of the methodology allows for an easy collection scheme that could be performed on a longitudinal basis to look at changes in albatross diets across years. Its true that the laboratory analysis was more complicated but a good prey library has now been established, so its entirely possible to collect samples on a yearly basis that could inform resource managers about changes in diet on yearly time scales. Given the limited time scales for sampling, we were not able to show interannual differences but with the collection of additional samples, it seems plausible that yearly differences could be detected.

F. CONCLUSIONS AND RECOMMENDATIONS: Overall, we accomplished 90% of what we proposed in this project. That is, to test whether a mechanistic link between oceanography and foraging ecology of North Pacific albatrosses could be established and whether these influences could explain the variation in breeding success. We did encounter one setback resulting from the unexpected death of a key colleague who was instrumental with remotely sensed oceanography products that we used in our models. His untimely death (and illness leading up to his death) set us back 3-6 months. However, we were able to forge ahead with the analysis to complete the majority of the project. The remaining analysis could be finished over the next year but we are happy to provide data or secondary products to other investigators creating large-scale models. As a next step, we envision developing a model to project what could happen to albatross populations if the TZCF moved north of its typical location as predicted in climate change scenarios. Its entirely possible that the population of Laysan and black-footed albatross at Tern Island could decline, either through emigration or natural attrition from poor breeding success. We recommend that similar studies be conducted at Midway Atoll or Laysan Island, which together comprise more than 80% of the world's population of Laysan and black-footed albatrosses. These locations are closer to the existing TZCF location and thus may not feel the effects of longer commutes if the TZCF continues to move further north.

- G. OUTREACH:** Currently, we have not produced any non-technical products for outreach to the general public. However, we are collaborating with Dr. Randy Kochevar of Hopkins Marine Station (of Stanford University) who has an NSF-funded program that uses tracking data from various marine predators to excite and teach high school kids about the oceans. Dr. Shaffer has agreed to serve as a resident scientist and offer assistance and interpretation with aspects related to seabird biology. Dr. Kochevar is using the same albatross tracking data we analyzed for this project. At some point in the near future, I plan to visit one of the schools he is working with in Monterey to talk about the implications of climate change and how we see patterns in the albatross data that indicated a change in oceanic conditions. In addition, Dr. Shaffer is faculty in the Biological Science Department at San Jose State University who teaches topics in Physiological Ecology, Ecology, and eventually Conservation Biology. He plans to use examples of this work in lectures and possible lab exercises. Finally, we are happy to provide PICCC with example materials or reports geared for public outreach.
- H. SCIENCE OUTPUTS:** We currently have a draft manuscript entitled '**Fronts, Food, and Fitness: Linking Environment to Reproduction in Two North Pacific Albatross Species**' by Thorne et al. that will be submitted to one of the following peer-reviewed journals: *Progress in Oceanography*, *Marine Ecology Progress Series*, *Diversity and Distributions*, or *Journal of Animal Ecology*. The planned submission date is June 2014 but we have included the draft with this report. We envision one additional manuscript to come from this analysis that will focus on future predictions based on different climate change scenarios. In addition to the draft manuscript, a total three presentations were given at scientific meetings including PICES (sponsored by the North American Marine Science Organization; October 2012, Japan) and Pacific Seabird Group (Feb 2013 in Portland, OR & Feb 2014 in Juneau, AK). The abstracts for these presentations are included with this report. The fatty acid signature analysis supported by this grant is part of the dissertation of Melinda Conners. Melinda is a doctoral student of Dr. Shaffer at UCSC. The analysis will form Chapter 2 of the thesis and will ultimately be published in a peer-reviewed journal with likely submission in spring 2015.

I. KEY FIGURES: Below are key figures from this work.

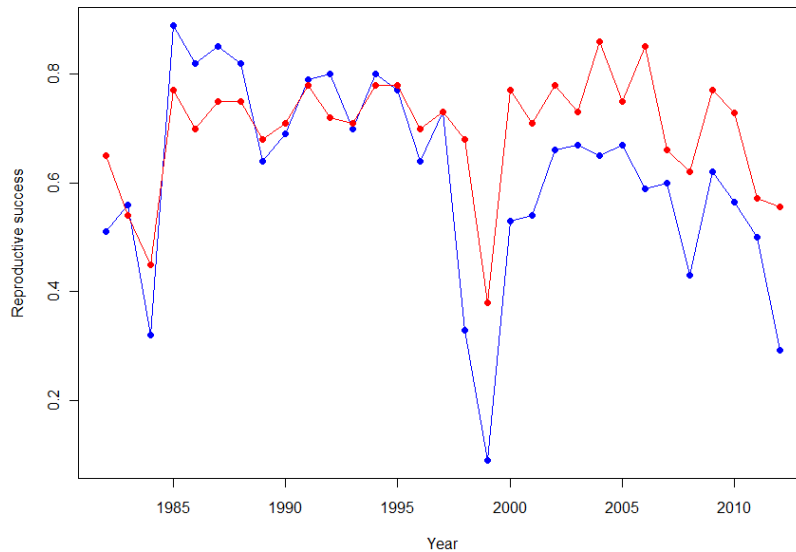


Figure 1: Reproductive success of Laysan and Black-footed albatrosses from 1982-2012 breeding at Tern Island, French Frigate Shoals, Northwest Hawaiian Islands. The data were provided by the US Fish and Wildlife Service, Migratory Bird Complex, Honolulu, Hawaii. Reproductive success was calculated by counting the island-wide number of chicks that fledged per eggs laid in each season. Note the dramatic declines in the 1983-84, 1998-99, and 2011-12 breeding seasons the corresponded to moderate to strong La Niña events.

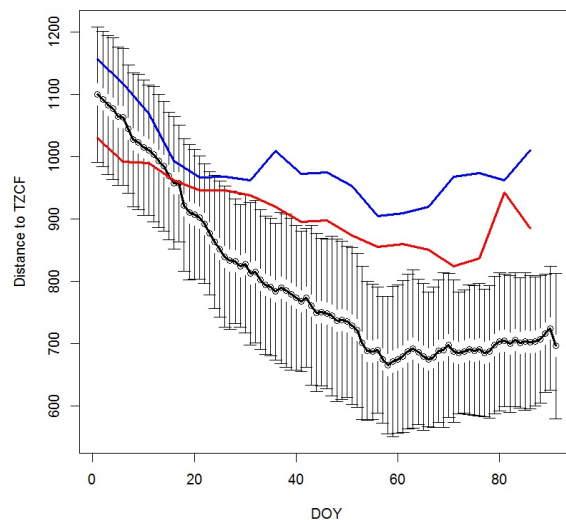


Figure 2: Daily distance of the Transition Zone Chlorophyll Front (TZCF) from Tern Island, French Frigate Shoals, Northwest Hawaiian Islands. Shown are the average of all years with error bars and for 1999 (blue) and 2008 (red). These two years correspond to the dramatic declines in reproductive success (Figure 1).

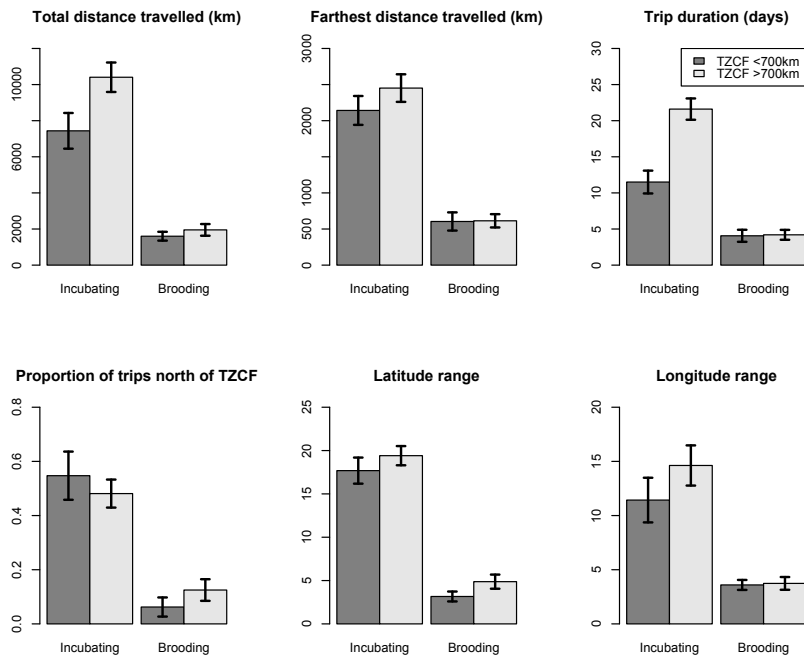


Figure 3: Trip metrics for Laysan albatrosses (means \pm SE) during the incubating and brooding periods when the TZCF was less than or greater than 700 km from Tern Island, respectively. Farthest distance travelled represents the farthest distance from Tern Island reached during trips, while the proportion of trip north of the TZCF reflects the proportion of each trip spent north of the front.

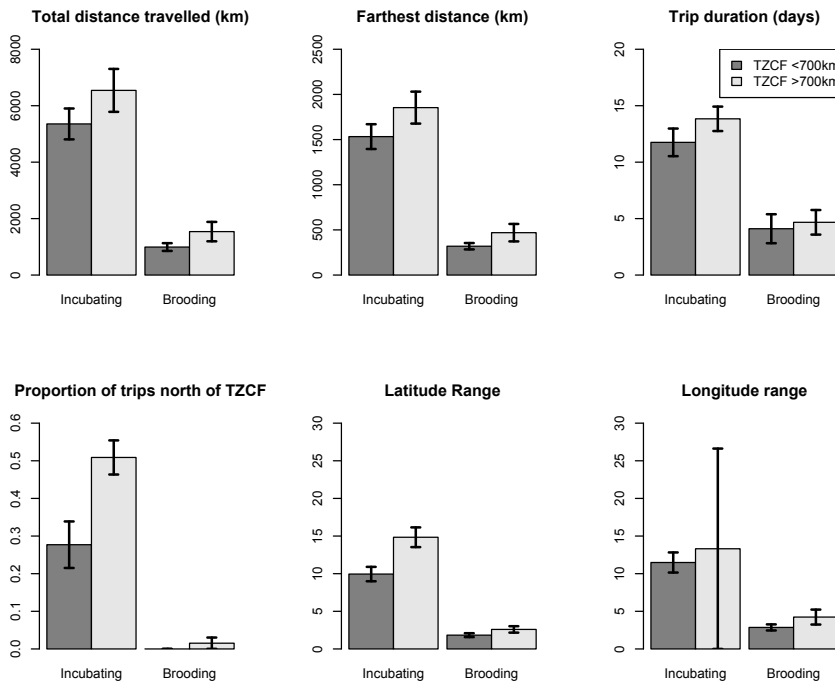


Figure 4: Trip metrics for Black-footed Albatrosses (means \pm SE) during the incubating and brooding periods when the TZCF was less than or greater than 700 km from Tern Island, respectively. Farthest distance travelled represents the farthest distance from Tern Island reached during trips, while the proportion of trip north of the TZCF reflects the proportion of each trip spent north of the front.

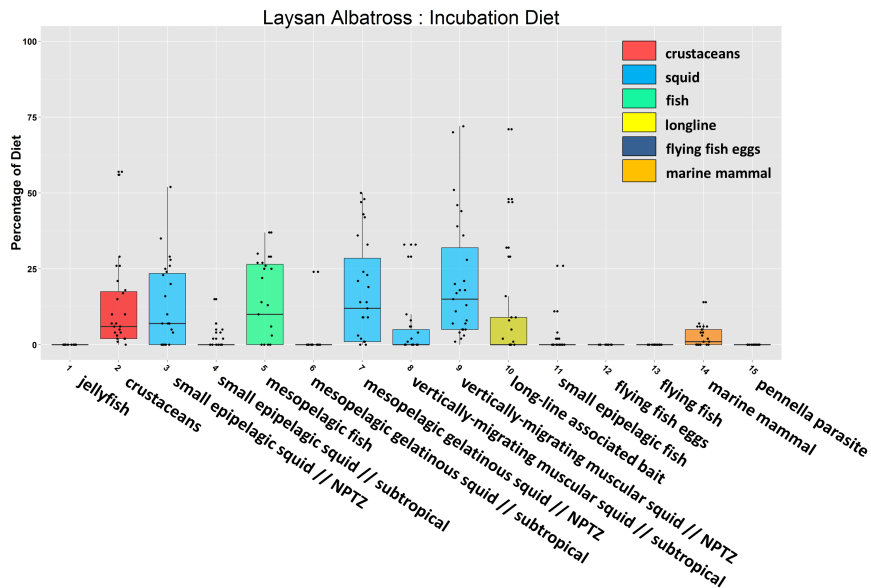


Figure 5: Example of prey determined from quantitative fatty acid signature analysis for Laysan albatrosses during the incubation phase.

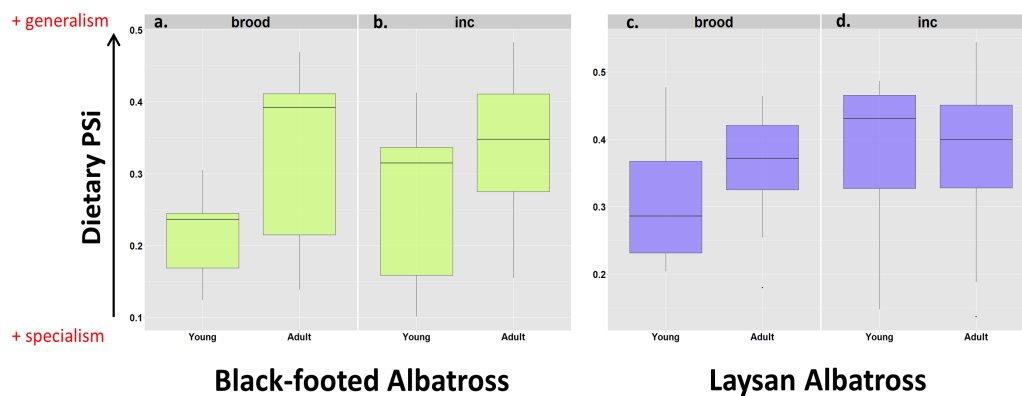


Figure 6: Dietary specialization of black-footed and Laysan albatrosses. The specialization is based on species, age class, and breeding phase differences.

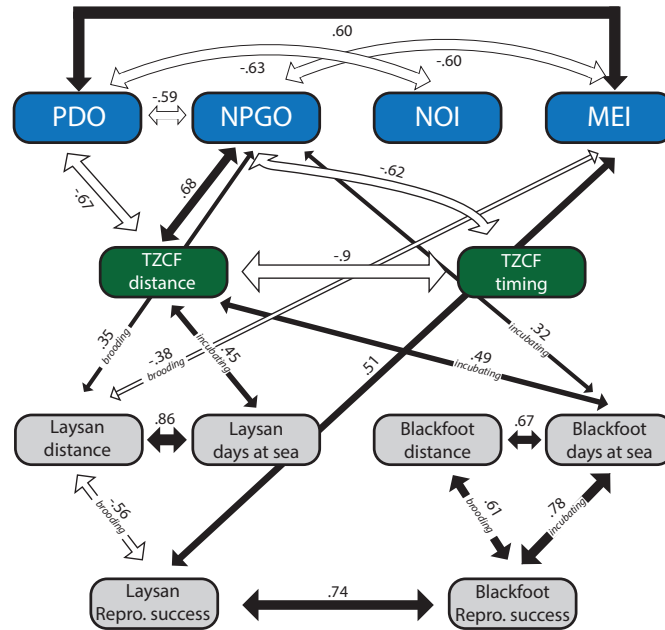


Figure 7: Schematic showing observed relationships between basin-scale climatic variables, variability in the TZCF, albatross trip metrics, and albatross reproductive success. Values represent Pearson's correlation coefficients with the thickness of the arrows reflecting the strength of the correlation. Only correlations coefficients greater than 0.3 are shown.

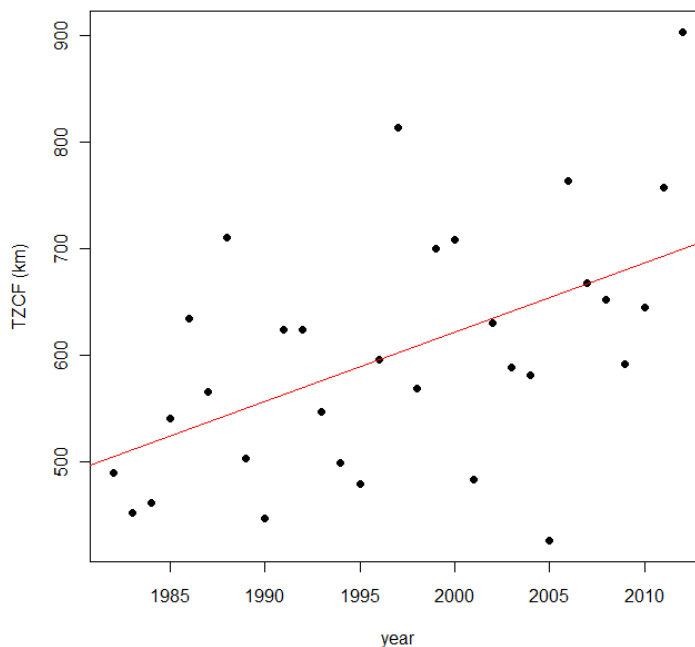


Figure 8: The relationship between minimum distance of TZCF from Tern Island (23.9°N, 166.3°W) between 1982-2012 (Adjusted $R^2=0.24$, $p=0.003$).