Title
On Climate Variability and Reproductive Success of a Central Pacific Albatross

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On climate variability and reproductive success of a central Pacific albatross

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Abstract

Breeding colonies of Mōlī (Phoebastria immutabilis) have shown reproductive declines in association with oceanographic and environmental variables such as the El Niño Southern Oscillation and North Pacific Gyre Oscillation. Reproductive responses to environmental extremes such as those associated with short-term climate events may provide clues to how the species will respond to long-term changes in global climate. This study examines reproductive success of Mōlī on Sand Island, Pihemanu, the largest breeding colony in the world, and finds that different colonies may respond differently to oceanographic variables such as the North Pacific Gyre Oscillation. Further study of the North Pacific Gyre Oscillation and its role in the position of the Transition Zone Chlorophyll front are necessary to more fully understand the dynamics of reproductive success throughout breeding colonies on islands in the subtropics.

Background

Mōlī (*Phoebastria immutabilis*), otherwise known as Laysan Albatrosses, are large pelagic seabirds that nest on islands in the subtropical Pacific. They are listed as "near threatened" on the IUCN Red List and the Agreement on the Conservation of Albatrosses and Petrels (Naughton, 2010). Over 70% of the world's breeding population (400,000-450,000 breeding pairs) nests on Pihemanu (Midway Atoll), an atoll with three islets located within the Papahānaumokuākea Marine National Monument (Naughton, 2010).

Life History and Reproductive Success

Mōlī form socially monogamous pairs and females lay one egg per year in a ground nest in mid-November. Chicks hatch between late January and early February, after which the brooding period begins. During the 2-3 week brooding period, the chick requires constant parental care and frequent feeding to ensure survival. At least one parent remains with the chick while the other forages. The two parents alternate between guarding the chick and foraging until late-February to early-March. After brooding comes the rearing period, when the chick is left alone at the nest while both parents forage. This period lasts four to five months until the chicks fledge in June and July (Kappes et al., 2015).

Successful reproduction is defined as a Mōlī chick advancing from egg to fledged adult. Reproductive failure is defined as when an egg is broken or otherwise fails to hatch, the parents die or desert the nest due to insufficient resources, or if a chick dies before fledging (e.g., drowning, heat exhaustion, insufficient food, or other causes) (Thorne et al., 2015).

Unlike most albatross species, Hawaiian albatrosses nest in oligotrophic waters and rely on dynamic soaring to reach distant, more-productive foraging areas (Suryan et al., 2008). Mōlī are known to forage for squid and other prey congregating in well-mixed, more-productive waters near the sub-Arctic transition zone and along the California and Alaska continental shelf regions (Suryan et al., 2008). During the incubation and rearing periods, adult Mōlī forage for weeks at a time to exploit these more distant foraging areas. However, during the brooding period in February, the fast-growing yet small chick must be fed every couple days, dramatically shortening the distances adults can travel (Thorne et al., 2015).

Implications

Climate change is well documented and average air and sea surface temperatures are projected to rise over time (IPCC, 2022). In the Hawaiian islands alone, average air temperatures have increased by 1˚F in the past century (EPA). Climate change in the subtropical islands near Hawaii is associated with more frequent and extreme events such as storm surges, flooding, and extreme heating (O'Connor et al., 2015).

Researchers are becoming increasingly concerned about the potential effects of climate change on different species, including albatross (Kappes et al., 2010). Analyzing historic and present day climate extremes may provide clues as to what can be expected for different species in a warming world (Thorne et al., 2015).

This kind of analysis is particularly important for sentinel species (Hazen et al., 2019) like Mōlī. As easily-observable top predators that traverse large distances, they could act as indicators for the effects of climate change throughout the Pacific Ocean.

Preliminary analysis of US Fish and Wildlife Service data shows that Mōlī reproductive success appears to be declining in some colonies. Although there are other variables that could be contributing to this reproductive decline, I chose to focus on climate variables due to the role of the albatross as a sentinel species in the Pacific Ocean.

Goals

In this study, I examine potentially important oceanographic and environmental variables that could be affecting reproductive variability in Mōlī on Pihemanu, including basin-scale climate indices such as the Multivariate ENSO Index (MEI), and North Pacific Gyre Oscillation Index (NPGO), as well as local island conditions such as air temperature, precipitation, and wind speed. I also provide management suggestions for Mōlī on Pihemanu with the hope of improving or stabilizing the downward trend in reproductive success.

Local Variables

Heat

Mōlī chicks have physiological and behavioral adaptations to heat. Historically, the climate on Pihemanu has been mild and consistent, with maximum air temperatures of 75° to 86° F and near constant ocean breezes. Soil temperatures have reached highs of 104° F. In mild weather, eggs and young chicks stay cool and sheltered from the sun and rain within their protective ground nests. When chicks become too big to brood, they have been known to sit on their heels with webbed feet in the air to cool off from high soil temperatures. Chicks have also been observed panting on particularly hot days (Howell and Bartholomew, 1961).

With climate change, extreme heat events are expected to become more frequent (IPCC, 2022), and could reach levels that adults and chicks cannot tolerate. It is projected that higher global atmospheric temperatures could increase heat stress for adult seabirds and their offspring, although how different species will be affected is difficult to predict due to differences in terrain, exposure, and tolerance to heat (Young et al., 2012). On high heat days, chicks on Pihemanu have been known to perish from dehydration (Sileo et al., 1990), as they quickly lose water while panting (Howell and Bartholomew, 1961).

Wind

While most albatross species breed in the southern hemisphere where wind speeds are among the highest on Earth, Hawaiian albatross species are unique in that they inhabit a region characterized by low to moderate average wind speeds (Suryan et. al, 2008). Wind speed is an important environmental variable for albatross, as they rely on strong winds to get off the ground and travel immense distances with minimal effort, in a process known as dynamic soaring (Sachs, 2005). Consistent breezes are also postulated to help with advection on hot days, cooling birds that would otherwise be overheated (Howell and Bartholomew, 1961).

However, wind speeds are not always consistent from year to year. Basin-scale environmental indices such as El Niño Southern Oscillation (ENSO) are driven by the strengthening or weakening of trade winds (Brown et al., 2001). Some climate models predict that wind speed will decline across equatorial regions in the next sixty years, particularly in the eastern and northern Pacific Ocean (McInnes, Erwin and Bathols, 2011). These are particularly important foraging areas for Mōlī and other Hawaiian albatross species (Suryan et. al, 2008).

Precipitation

It is well-documented that extreme precipitation events can lead to chick and adult deaths. As far back as 1960, flooding events have been known to destroy nests and chicks (Howell and Bartholomew, 1961). More recently, the Tōhoku tsunami in 2011 flooded 29% of Pihemanu and inundated 219,631 Mōlī nests (Reynolds et al., 2017), resulting in thousands of chick and adult deaths.

Typically, La Niña events are associated with heavy rainfall in the Hawaiian Islands, but in the past thirty years these wet La Niña winters have been much drier than normal (O'Connor et al., 2015). In recent years, the islands nearest to Pihemanu have shown an increase in dry days and decrease in heavy rains (Elison Timm *et al.*, 2021). It is unclear how mean precipitation on Midway could be altered in a changing climate, but some models predict that as sea surface temperature rises, mean precipitation and the variability of that precipitation in the central Pacific will also increase (Watanabe, Kamae and Kimoto, 2014).

Basin-Scale Variables

MEI.v2

The El Niño Southern Oscillation (ENSO) is a naturally-occurring climate event that affects weather and rain patterns worldwide. During normal conditions in the Pacific Ocean, trade winds along the equator transport warm surface water west towards Asia, allowing cool, nutrient-rich water to rise to the surface along the west coast of the Americas in a process known as upwelling. During El Niño events, these trade winds weaken, decreasing coastal upwelling in the eastern pacific. During La Niña events, the trade winds become stronger, creating more upwelling in the eastern pacific (Brown et al., 2001).

The Multivariate ENSO Index (MEI) is an index that measures El Niño/La Niña conditions using atmospheric and oceanographic variables such as sea surface temperature, sea level pressure, and outgoing long wave radiation. This results in an overlapping bimonthly numeric value, with values above 0.5 corresponding to El Niño events, and values below -0.5 corresponding to La Niña events (NOAA). While there are other indices available to describe ENSO, I chose the Multivariate ENSO Index because of its comprehensive nature and its use in similar studies on nearby islands (Thorne et al., 2015).

Like the local climate variables, ENSO is likely to change with a changing climate. However, how ENSO will shift is still uncertain (Collins et al., 2010), with predictions dependent on the model used (Chen et al., 2017). Some studies have pointed out that El Niño events in previous decades peaked in the eastern Pacific, but are peaking in the central Pacific in recent decades and suggest this could become more frequent in projected climate scenarios. This has unclear consequences for the other oceanographic and atmospheric variables associated with ENSO (Di Lorenzo et al., 2010). However, it is unclear if this trend is a product of anthropogenic climate change or natural variability (Chen *et al.*, 2017).

NPGO

The North Pacific Gyre Oscillation (NPGO) is a relatively newly described climate pattern that sheds light on previously unexplained fluctuations in sea surface temperature, nutrients, salinity, and chlorophyll. Like the ENSO, the NPGO is driven by variations in winds and upwelling. However, it provides a more complex index that better correlates with biological fluctuations such as phytoplankton concentrations in the North Pacific, which in turn affect higher trophic levels (Di Lorenzo *et al.*, 2008).

The NPGO is characterized by two gyres: the Alaskan Gyre to the north and the Subtropical Gyre to the south. These gyres are separated by the North Pacific Current (NPC) flowing east along approximately 40°N. The strength of this current varies seasonally and annually. The NPGO index measures the strength of this gyre-scale circulation, describing the strengthening and wearing of the sub-tropical and sub-polar gyres (Di Lorenzo *et al.*, 2008). When the NPGO is in its positive phase, this circulation is intensified and the NPC is strengthened. When the NPGO is in its negative phase, this circulation is weakened (Di Lorenzo *et al.*, 2008).

The NPGO has a strong association with the Transition Zone Chlorophyll Front (TZCF), an area of high primary productivity where warm, oligotrophic water from the subtropical gyre meets cold, well-mixed, nutrient-rich surface water from the subarctic gyre (Polovina et al., 2001). This convergence results in an aggregation of primary and secondary producers that attracts higher trophic level predators such as albatrosses (Polovina et al., 2001).

Positive NPGO is correlated with La Niña conditions and a northward displacement of the TZCF, while negative NPGO is correlated with El Niño conditions and southward displacement of the TZCF. This has mixed results for secondary producers such as squid (Alabia *et al.*, 2016), a preferred prey of Mōlī.

Climate change models predict a poleward shift in major ocean gyres, along with an overall expansion of the nutrient-poor subtropical biome and contraction of nutrient-rich temperate biomes (Polovina, 2011). This is projected to have mixed effects on primary productivity, with differing effects for different sub-regions of the Pacific Ocean (Sydeman et al., 2011).

Hypotheses

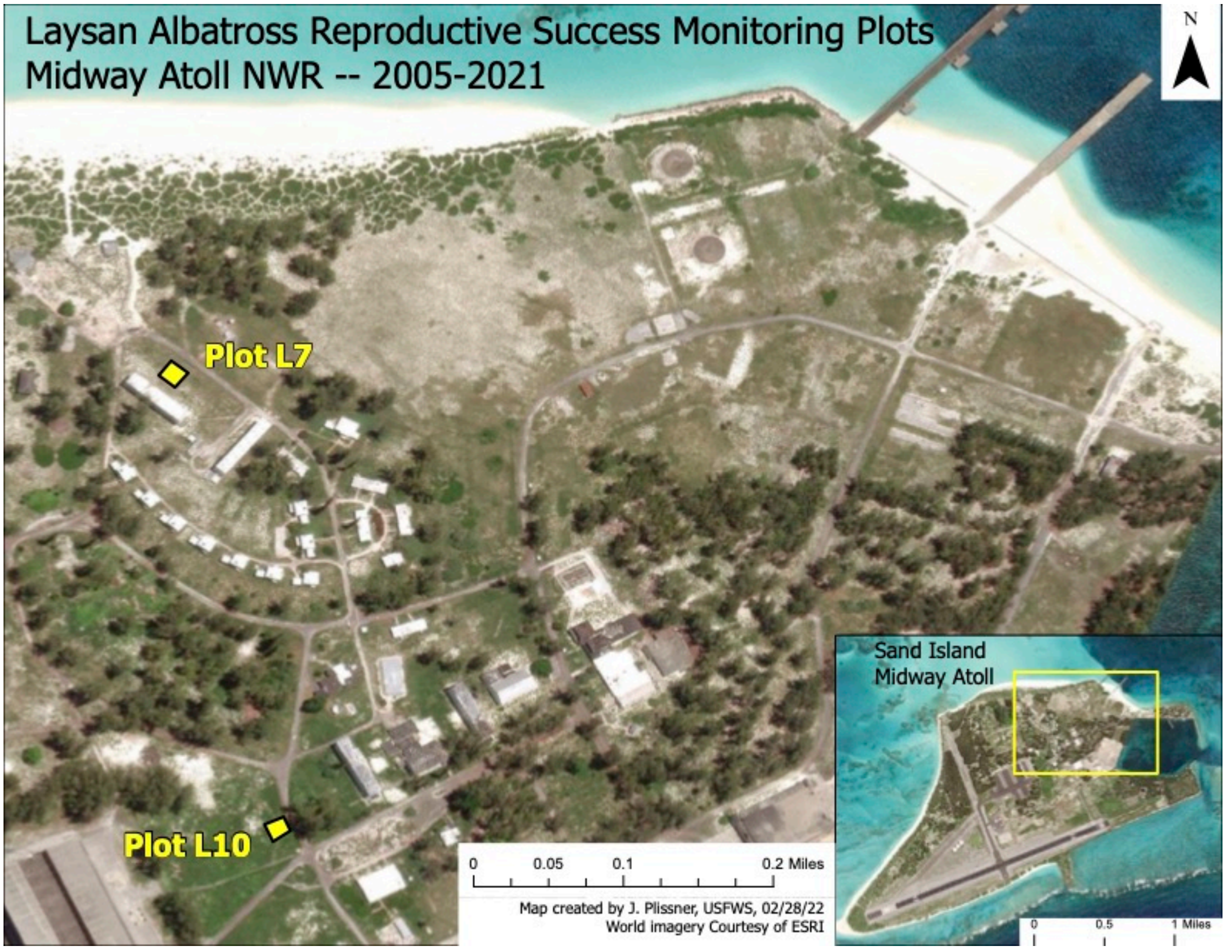
In this study, I hypothesize that increased average air temperatures and the number of extreme heat days will be associated with lower reproductive success, due to increased heat stress on adults and chicks. I also predict that increased precipitation will be associated with lower chick survival, due to the higher likelihood of flooding events. I expect that higher wind speed on the other hand will be associated with increased reproductive success, due to cooling effects and improved foraging.

Previous studies of Mōlī on Tern Island, just 750 miles southeast of Pihemanu, have demonstrated that reproductive success decreases when the NPGO is in a positive phase, TZCF is shifted farther north, and MEI is low (Thorne et al., 2015). It is hypothesized that this is because adult Mōlī on Tern Island do not have access to productive foraging waters during the brooding season. Thorne et al., (2015) highlighted the years 1998, 2008, and 2012 that showed marked declines in reproductive success and were associated with La Niña conditions and a northward displacement of the TZCF. Similar to studies conducted on Tern Island, I hypothesize that low MEI values and high NPGO values will be associated with decreased reproductive success.

Methods

Reproductive Success Monitoring

Between 2006 and 2021, annual reproductive data were collected from two plots in the Mōlī colony on Sand Island, Pihemanu (Figure 1). On average, Plot L7 contained 70 nests per year and Plot L10 contained 23 nests per year. Over the course of the study, a mean of 183 nests were monitored per year, with a minimum of 138 nests in 2007 and a maximum of 255 nests in 2019.



Laysan Albatross Reproductive Success Monitoring Plots
Midway Atoll NWR -- 2005-2021

Map created by J. Plissner, USFWS, 02/28/22
World imagery Courtesy of ESRI

Figure 1: Reproductive monitoring plots on Pihemanu (Midway Atoll) are indicated in yellow. A map of the entire island is shown in the bottom right-hand corner.

Each plot was monitored twice a week during egg-laying and once every seven to ten days during the rest of the breeding season. When a hatched chick was first observed, the date was recorded and the chick was banded. During each subsequent visit to the plot, volunteers checked for the presence of the chick. Crushed eggs or dead chicks were recorded along with the date observed. In the case of a missing chick, it would be searched for in the subsequent three visits to the plot before it was marked as a reproductive failure.

Chick monitoring continued until all of the chicks fledged for each year. A chick was considered fledged if it was fully feathered and disappeared from the plot in June, July, or later. If a chick was last seen with extensive downy feathering and disappeared in June or July, it was marked as a reproductive failure.

Reproductive success was calculated by dividing the number of successfully fledged chicks in a given year by the total number of eggs laid that year. The equation used was: *Reproductive Success = Total Fledged / Total Nests*. Preliminary analysis of a basic time series plot shows that reproductive success appears to be trending downward over time (Figure 2), even as the total number of nests has increased (Figure 3).

Because eggs are laid in November and chicks fledge the following June or July, "hatch year" is defined as the period between November of one calendar year through July of the next calendar year. November through January were classified as "Egg," February was classified as "Brood," and March through July were classified as "Rear" to represent the three phases of the breeding season: egg-laying and incubation, brooding, and rearing.

Summarizing Oceanographic and Environmental Data

Air temperature, wind speed, and precipitation were recorded at the Midway Airport (https://www.ncei.noaa.gov/access/search/data-search/local-climatological-data) every few minutes from 2006 to 2021. Using the programming language R (R Core Team 4.1.2), I loaded each yearly dataset and summarized it by phase of the breeding season and hatch year. In this study, I used air temperature, wind speed, and precipitation values recorded during the breeding season (November through July) only.

Variable 1: Average Temperature

To calculate average temperature, "daylight hours" were set between 6:00am and 6:00pm daily to account for maximum daylight throughout the breeding season. The "aggregate" function in R was used to take the mean daytime temperature (± SD) of each phase of the breeding season and hatch year overall.

Variable 2: Max Temperature Days

I postulated that even one extreme temperature day, or an increase in extreme temperature days per year could cause enough heat stress to kill chicks. These extreme values would not be accounted for in a mean calculation. To satisfy this, a “hot day” was classified as a daytime temperature higher than two standard deviations above the mean, which ended up being 84.73° F. The number of “hot days” were summed per year.

Variable 3: Average Precipitation

Daily precipitation was calculated by summing hourly precipitation readings for each day. The “aggregate” function in R was used to determine the mean total daily rainfall (± SD) for each phase of the breeding season and hatch year overall.

Variable 4: Maximum Precipitation Days

Similar to temperature, it was theorized that a greater number of “high precipitation days” could lead to flooding and, thereby, impact chick survival. To evaluate this theory, a day was classified as “rainy” when the daily rainfall value was greater than two standard deviations above the mean, which ended up being 2.12 inches. The number of “rainy” days were summed per hatch year.

Variable 5: Wind Speed

Erroneous data readings were discarded, by applying a filter that removed any wind speed over the global maximum of 253 miles per hour, and mean (± SD) wind speed was calculated for each phase of the breeding season and hatch year.

Variable 6: MEI

MEI values (https://psl.noaa.gov/enso/mei/) are calculated on a bimonthly basis, with a value for January-February, February-March, March-April, and so on. To calculate a single MEI value per hatch year, the mean was calculated for all values in a given hatch year. Any value above 0.5 was considered an El Niño year, and any value below -0.5 was considered a La Niña year.

Variable 7: NPGO

Similar to MEI, NPGO values (http://www.o3d.org/npgo/) are calculated monthly. To come up with a single NPGO value per hatch year, the mean was calculated for all values in a given hatch year. Positive values of the NPGO correspond with an expansion of the North Pacific Gyre, while negative values correspond to a contraction of the North Pacific Gyre.

Analysis

	Reproductive Success	Avg. Temp	High Temp Days	Avg. Precip	High Precip Days	Avg. Wind Speed	MEI
Avg. Temp	-0.18						
High Temp Days	0.09	0.23					
Avg. Precip	0.01	-0.60**	-0.02				
High Precip Days	0.13	-0.50*	-0.09	0.95***			
Avg. Wind Speed	0.20	-0.47 .	0.09	0.47 .	0.47 .		
MEI	-0.18	-0.13	0.16	-0.19	-0.30	-0.06	
NPGO	0.60**	0.12	0.23	-0.03	0.10	-0.01	-0.37

Table 1: Correlation coefficients of all local and basin-scale climate variables. Significance codes: 0.001 '***' 0.01 '**' 0.05 '*' 0.1 '.'

Variables	AIC	Change AIC	df	Adj. R-squared
Local only				
Avg. Temp . + High Temp Days + Avg. Precip* + High Precip Days*	-8.17	0.00	11	0.16
Avg. Temp + Avg. Precip . + High Precip Days .	-7.57	0.60	12	0.10
Avg. Temp + High Temp Days + Avg. Precip* + High Precip Days . + Avg. Wind Speed	-6.17	2.00	10	0.08
Basin-scale only				
NPGO*	-13.41	0.00	14	0.31
MEI	-6.87	-6.54	14	-0.04
Basin-scale + Local				
NPGO* + Avg. Temp	-13.17	0.00	13	0.34
NPGO* + Avg. Wind Speed	-12.53	0.64	13	0.31
NPGO* + Avg. Temp + Avg. Precip + High Precip Days	-11.72	1.45	11	0.33
NPGO + Avg. Temp . + High Temp Days + Avg. Precip + High Precip Days	-10.53	2.64	10	0.30
NPGO + Avg. Temp + High Temp Days + Avg. Precip + High Precip Days + Avg. Wind Speed	-8.65	4.52	9	0.23
MEI + Avg. Temp . + High Temp Days + Avg. Precip* + High Precip Days .	-6.85	6.32	10	0.12
MEI + Avg. Temp + High Temp Days + Avg. Precip . + High Precip Days . + Avg. Wind Speed	-4.85	8.32	9	0.02

Table 2: A selection of Generalized Linear Model results. AIC, Δ AIC, degrees of freedom, and adjusted R^2 values are reported for each model. Models are split into three groups: local variables only, basin-scale variables only, and models with a combination of basin-scale and local variables.

Pearson's correlation coefficients were used to examine relationships between each predictor variable pair, and between those variables and reproductive success. Generalized Linear Models (GLMs) were used to examine the association between predictor variables and reproductive success, as well as combinations of variables and reproductive success. For all GLMs, Akaike Information Criterion (AIC) was used to select variables for the best fit model. GLMs were performed using the base R Statistical package. Over 105 models were run and summarized in total. Due to the relatively small sample size, the significance level was set at $p = 0.1$ for all analyses.

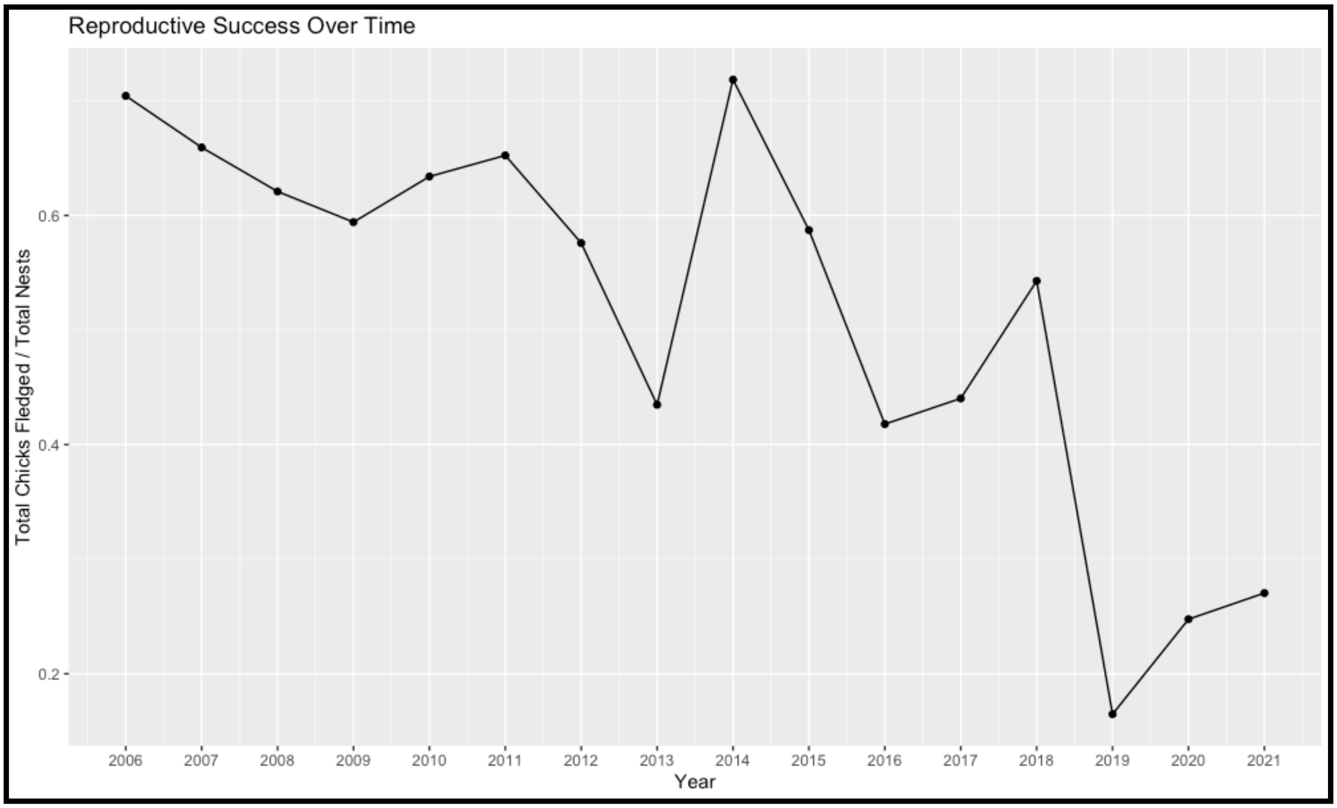


Figure 2: Basic time series plot of reproductive success over time. Reproductive success was calculated for each hatch year using the formula: *total chicks fledged / total nests = reproductive success*

Results

A basic time series plot shows that reproductive success in the two study areas on Pihemanu have decreased over time (Figure 2). This is despite an increase in number of nests over time (Figure 3).

Local Variables

Average precipitation ($p = 0.01$), high precipitation days ($p = 0.05$), and average wind speed ($p = 0.1$) were all negatively correlated with average air temperature, with correlation coefficients of -0.60, -0.50, and -.47 respectively (Table 1). Average precipitation was correlated with high precipitation days ($p = 0.001$), but average temperature was not significantly correlated with high temperature days. Finally, average precipitation and high precipitation days were both positively correlated with average wind speed ($p = 0.1$), with correlation coefficients of 0.47. Figure 4 is a

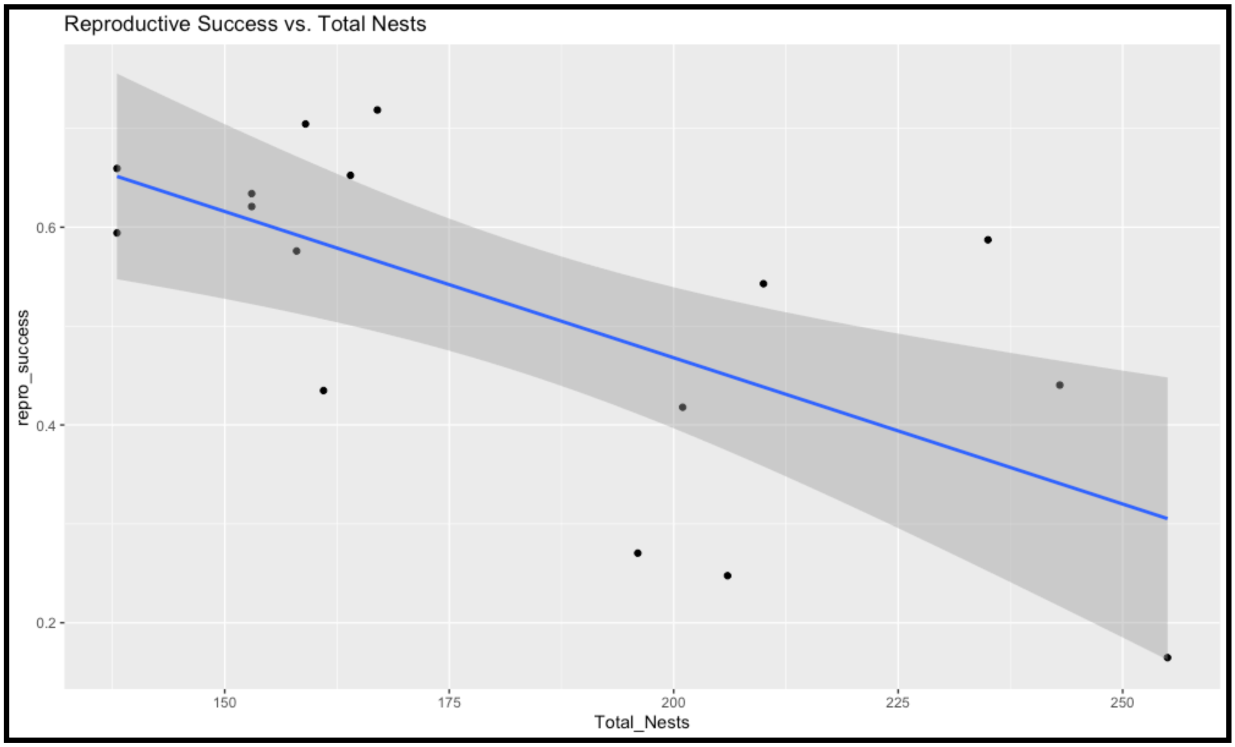


Figure 3: Scatterplot of reproductive success versus total nests. Total number of nests is shown on x axis. Reproductive success is shown on y axis. Even as total nests increase, reproductive success declines. Trend line was calculated using y ~ x linear regression in R.

visual demonstration of correlations between different environmental variables.

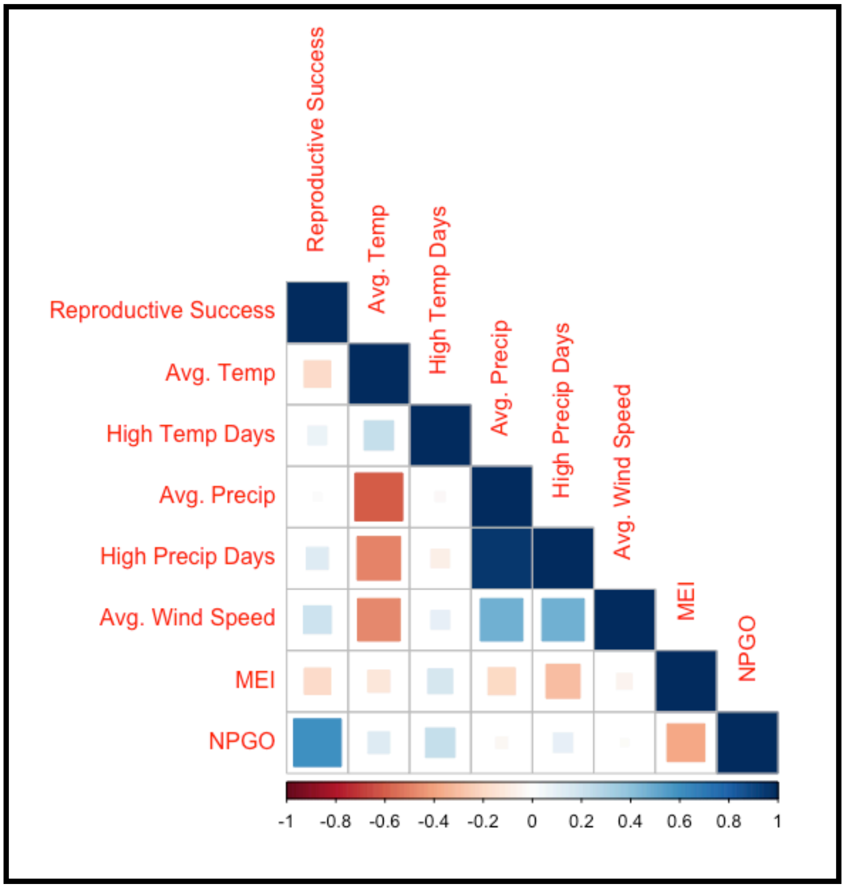


Figure 4: Correlation plot of all local and basin-scale environmental variables. -1 is a perfect negative correlation and +1 is a perfect positive correlation. Darker colors and larger squares represent stronger correlations.

Of the General Linear Models that only included local variables (Table 2), the most parsimonious model included average temperature, high temperature days, average precipitation, and high precipitation days. Average precipitation and high precipitation days were both significant (p = 0.05), as well as average temperature (p = 0.1). While average temperature and average precipitation appeared to have a negative association with reproductive success (slope of -0.1 and -3.06 respectively), max precipitation days had a slightly positive

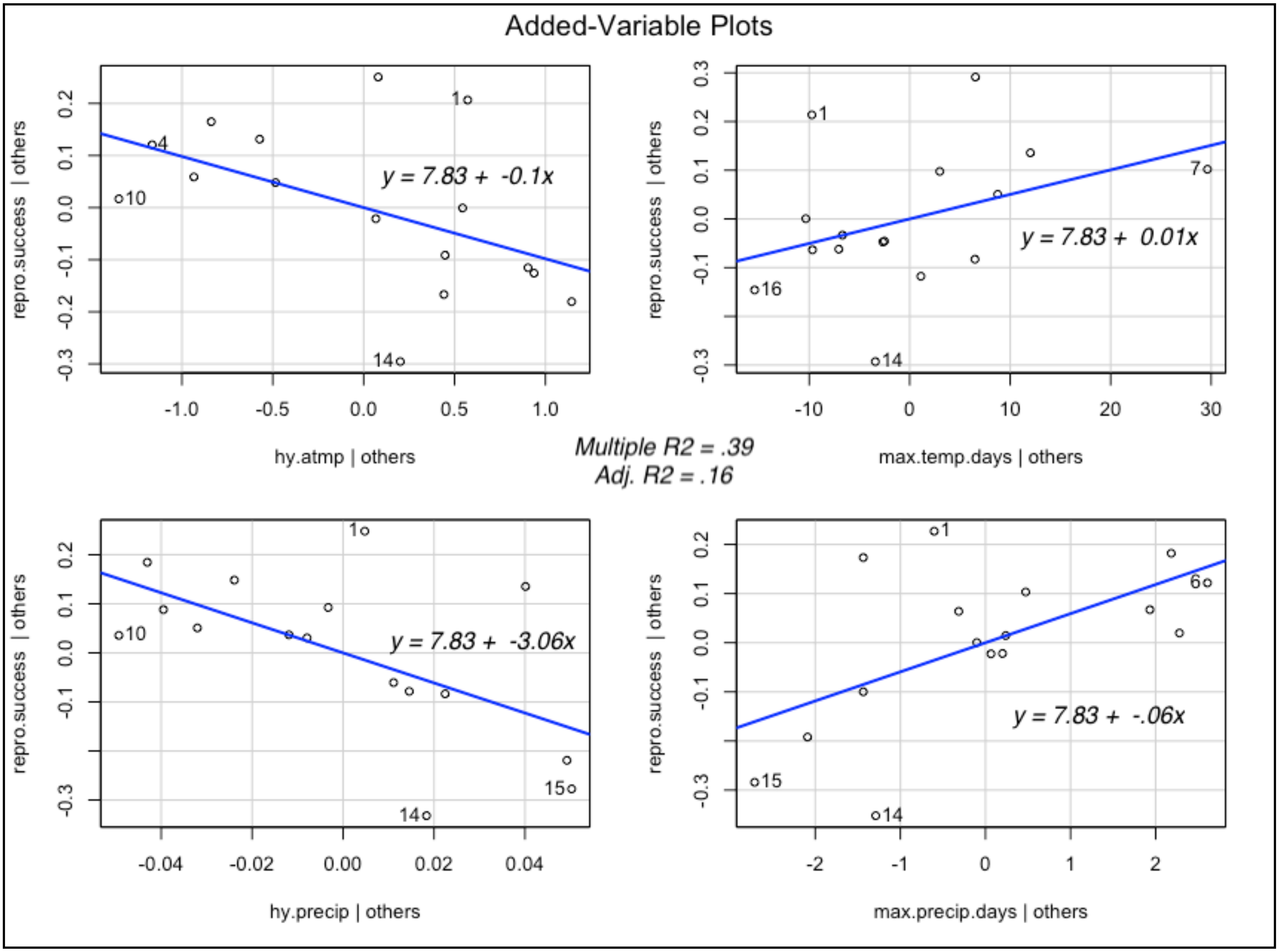


Figure 5: Added-Variable Plot of best fit model for local variables only, which includes average air temperature, average precipitation, high temperature days, and high precipitation days. Y axis on all graphs shows reproductive success. Top left: x = average air temperature (p = 0.1). Top right: x = high temperature days. Bottom left: x = average precipitation (p = 0.05). Bottom right: x = high precipitation days (p = 0.05). R^2 = 0.39. Adj. R^2 = 0.16. Line formulas are shown on each graph.

association (slope of 0.05) with reproductive success (Figure 5). This model had an R^2 value of 0.16 (Table 2).

Basin-Scale Variables

NPGO was significantly correlated with reproductive success (p = 0.05, with a coefficient of 0.60). NPGO was not significantly correlated with any other environmental variables (Table 1).

Of the General Linear Models that included basin-scale variables (Table 2), NPGO was the only variable that came out as significant (p = 0.05). Models including NPGO had AIC values that were much lower than any of the local variable models, or the models including MEI. NPGO versus reproductive success alone was significant (p = 0.05) with a positive slope of 0.08 (Figure

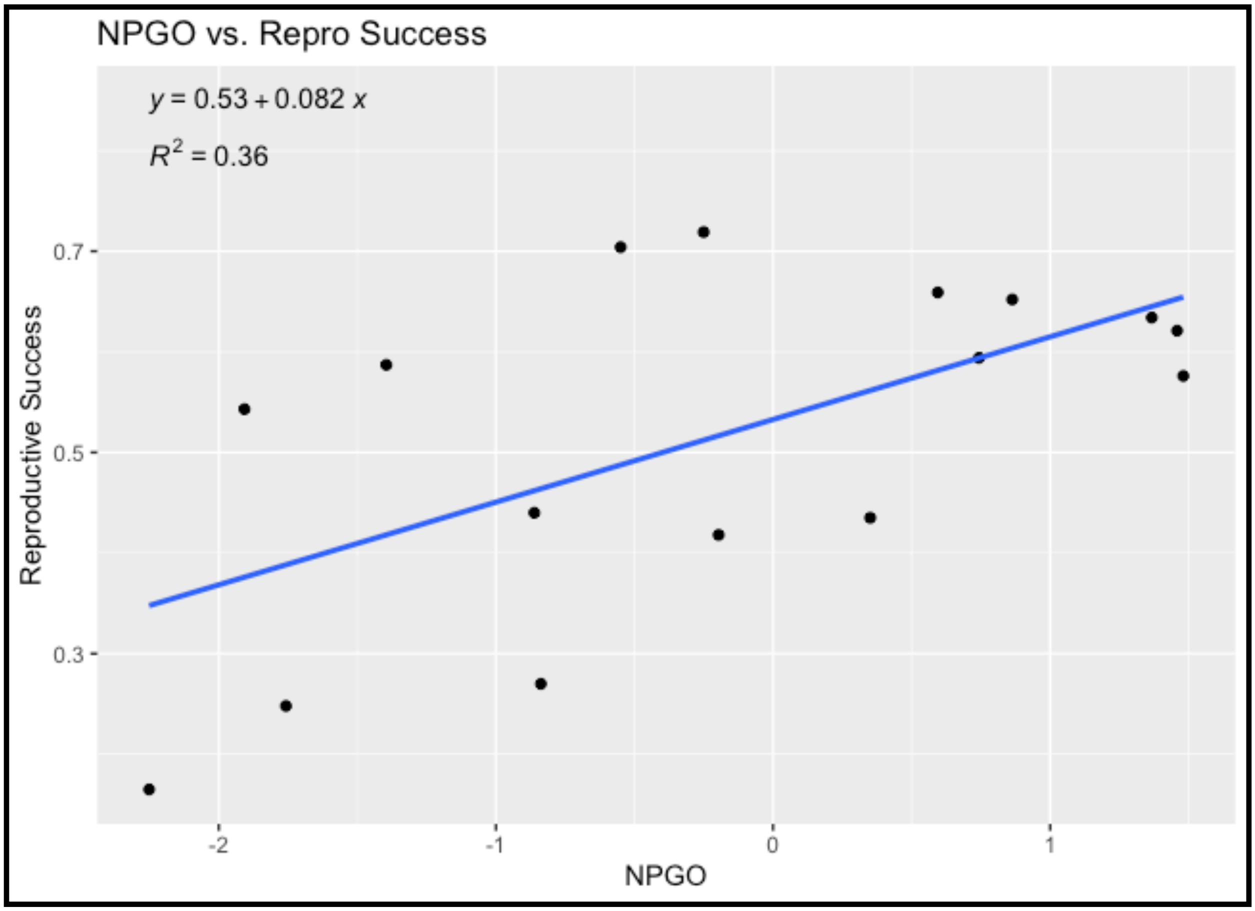


Figure 6: Generalized Linear Model of NPGO ~ Reproductive Success. x = NPGO (p = 0.05), y = Reproductive Success. Adj. R^2 = 0.31. $y = 0.53 + 0.08x$

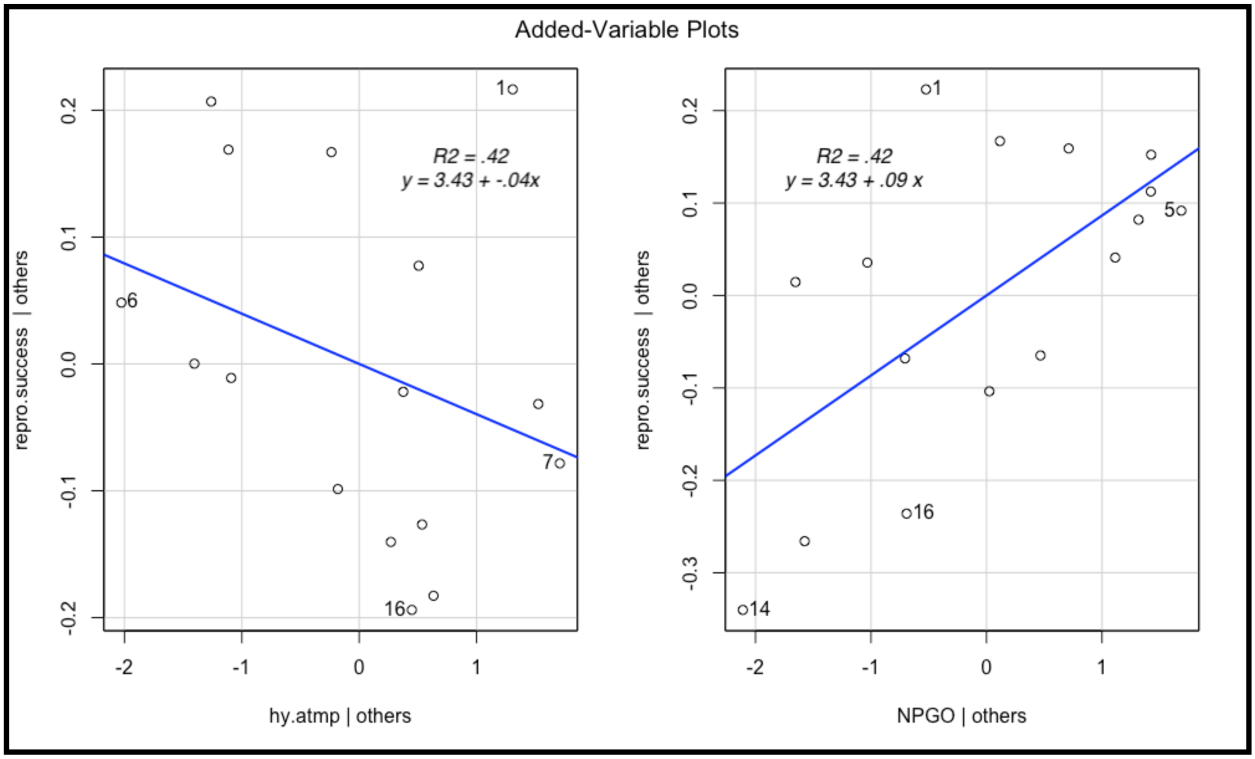


Figure 7: Added-Variable Plots of Reproductive Success ~ NPGO + Avg. Air Temperature. Both graphs show reproductive success on the y axis. Left: x = avg. air temperature. $y = 3.43 - .04x$. Right: x = NPGO (p = 0.05). $y = 3.43 + .09x$. Adj. R^2 = 0.34.

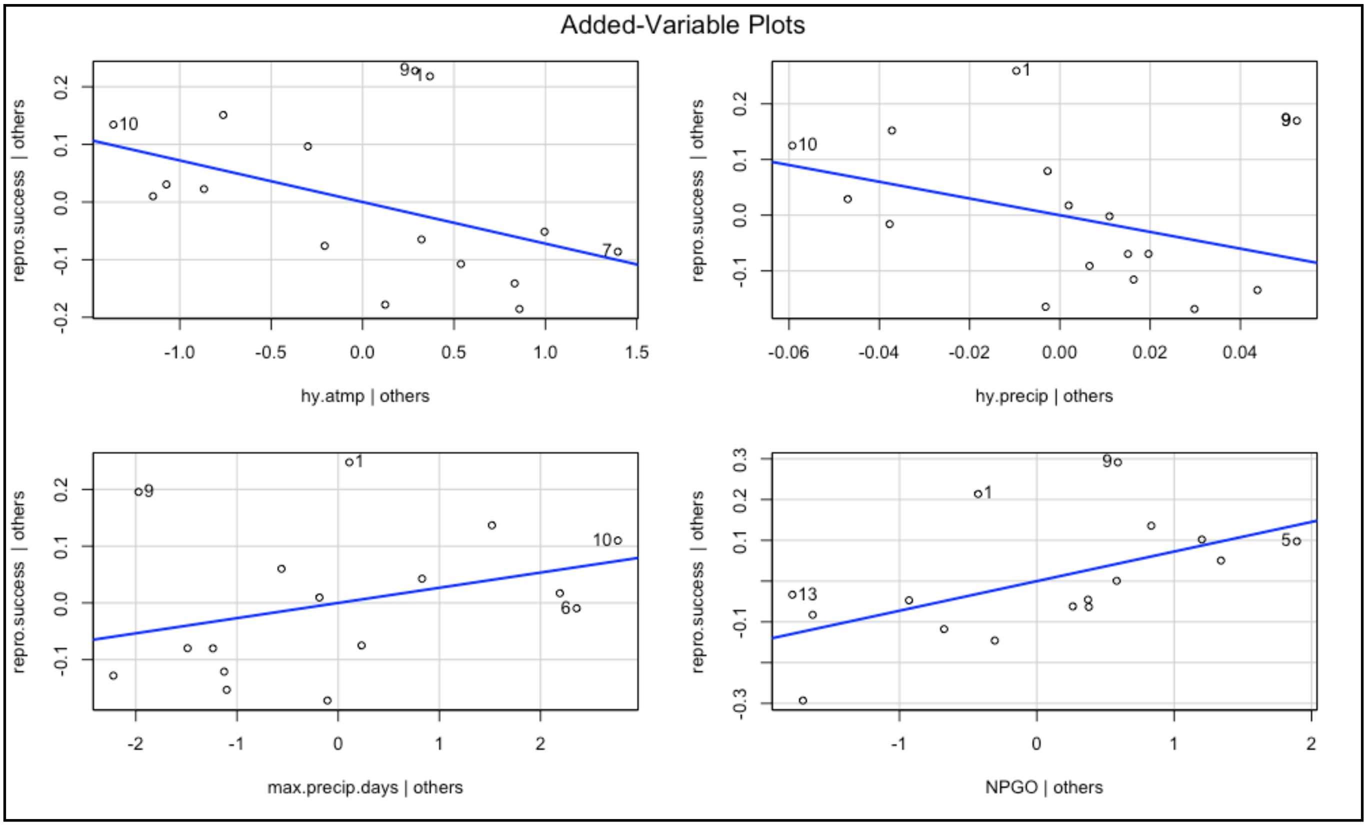


Figure 8: Added-Variable Plots of Reproductive Success ~ NPGO + Avg. Air Temperature + Avg. Precipitation + High Precipitation Days. All graphs show reproductive success on the y axis. Top left: x = avg. air temperature. *y = 5.93 - .07x*. Top right: x = avg. precipitation. *y = 5.93 - 1.50x*. Bottom left: x = high precipitation days. *y = 5.93 + .02x*. Bottom right: x = NPGO (p = 0.05). *y = 5.93 + .07x*. Adj. $R^2 = 0.33$.

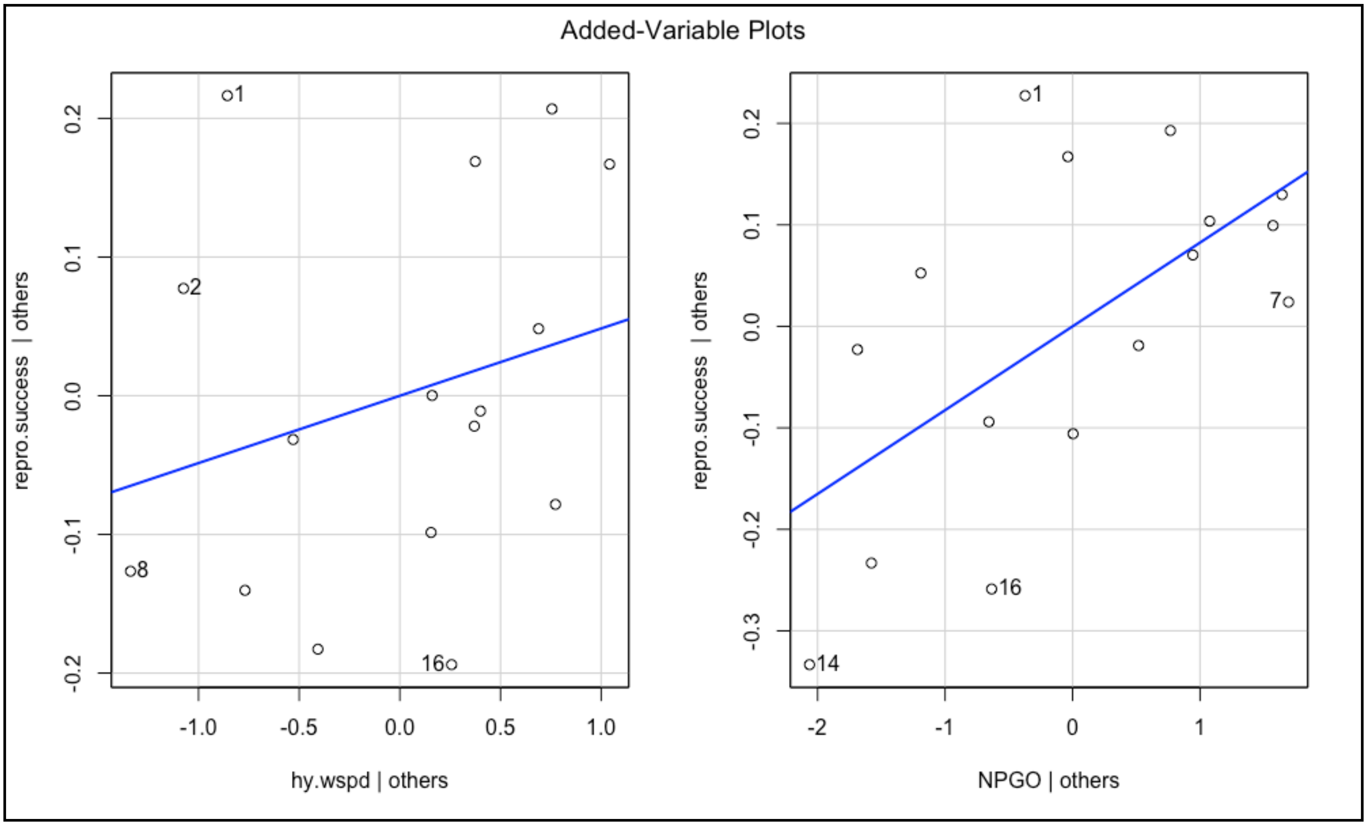


Figure 9: Added-Variable Plots of Reproductive Success ~ NPGO + Avg. Wind Speed. Both graphs show reproductive success on the y axis. Left: x = avg. wind speed. *y= -.03 + .05x*. Right: x = NPGO. *y= -.03 + .08x*. Adj. $R^2 = 0.31$.

6) and an adjusted R^2 value of 0.31.

The most parsimonious model of two values or more included NPGO and average temperature, with NPGO significant ($p = 0.05$) and an adjusted R^2 value of 0.34 (Figure 7). Other parsimonious models included NPGO ($p = 0.05$) and wind speed ($R^2 = 0.31$) (Figure 9), as well as NPGO and average precipitation, high precipitation days, and average temperature ($R^2 = 0.33$) (Figure 8).

Discussion and Management Suggestions

Local Variables

Direct impacts like overheating and rainfall appear to show a negative relationship with Mōlī reproductive success on Pihemanu. Average temperature, average precipitation, and high precipitation days were all significant at various levels in multiple models. However, it appears that these local, direct impacts are not as important a concern as global environmental conditions that affect foraging on the open ocean.

In models including local variables only, heat and rainfall did come out as significant but the R^2 values were low (Table 2). It is unlikely that much of the variability in reproductive success can be explained by these local variables alone. However, models including the NPGO index that also included one or more local variables had lower AIC values and higher R^2 values. In these models, the local variables did not come out as significant; however, they explain more of the variability in the data. Models including NPGO as well as average air temperature, average precipitation, or a combination of these all had R^2 values that were slightly higher than the model with NPGO alone. However, some of this may be due to correlations between one or more local variables. That being said, local actions can be taken on Pihemanu itself to reduce impacts to birds.

One such action to avoid heat stress would be to prioritize creating shade for the birds, either naturally or artificially. While this study only takes air temperature into account, it is likely that soil temperature is much hotter. Resource managers will need to take increased heat stress into account when considering the removal of native or non-native vegetation. A cost-benefit analysis would be beneficial when making decisions to remove plants from the island, as shade will become more and more critical as global temperatures rise. The data reported in this study is bolstered by informal observations by resource managers from US Fish and Wildlife Service, who report Mōlī will congregate in shaded areas on hot days. While likely expensive, it may also be worthwhile to consider erecting artificial shade structures that allow breezes to circulate underneath to help cool off nesting birds and their chicks.

Because Pihemanu was once a military base, impermeable surfaces are not uncommon on the island. A suggestion to avoid serious flooding would be to remove impermeable surfaces from the island, in order to reduce flooding as much as possible. Another suggestion might be to add drainage channels, so water doesn't pool and inundate nests.

Basin-scale Variables

According to this preliminary analysis, NPGO appears to be positively associated with reproductive success on Pihemanu. This is in stark contrast to previous studies on Tern Island, which showed a negative association between positive NPGO and reproductive success. In particular, previous studies noted reproductive declines on Tern Island in 2008 and 2012, both years covered in this study. However, these years did not show marked reproductive declines in my sample.

Pihemanu is 750 miles roughly northwest of Tern Island, so it is possible that birds on Pihemanu are not as affected by a northward displacement of the TZCF associated with positive NPGO. It is also possible that the Mōlī on Pihemanu are foraging in a completely different area than the birds on Tern Island, exploiting more of the productive areas along the continental shelf of Alaska. Tracking data likely exist that would illuminate some of the differences between the birds on each island and their foraging behaviors. This would be an interesting area of further study.

However, while the NPGO was once a reliable indicator of fish stocks and other biological fluctuations, it is less stationary than previously thought and will likely become more unpredictable under a changing climate (Litzow et al., 2020). While it is important to take basin-scale indices into account when updating species status assessments or making other management decisions, it is also important to recognize that these indices may become unreliable over time if they are not continuously updated.

The results of this study show that not all Hawaiian albatross colonies should be assumed to respond to environmental variability in the same way. While these breeding habitats may seem similar and not too distant from one another, it is important for resource managers to recognize that each colony is different and take that into account when making decisions. However, there is considerable unexplained variance that requires further research.

Conclusions

The purpose of this capstone analysis is to provide an overview of the subject matter to determine next steps for a deeper dive into these questions. GLMs are a powerful tool, but they do not explain all possible relationships. It is possible that there are other relationships between these variables that could be better explained by a more complex model. GLMs also do not take time or space into account. Further study incorporating time and possible time lags would provide further detail to these results.

TZCF distance from the breeding colony needs to be investigated. This study used MEI and NPGO as a rough proxy for the general position of the TZCF in a given year. However, all three variables should be evaluated. The time constraints associated with this project did not provide an opportunity to calculate average distance to TZCF. Another limitation of this particular study was the use of yearly averages for climate indices that vary seasonally. Additional study may require finer detail.

This study shows that while local variables are important, the impacts of basin parameters (NPGO) show a stronger influence. Anthropogenic climate change will impact sea surface temperatures, which will in turn affect the winds and currents that drive gyres and other basin-scale variables like the NPGO. While Pihemanu may be under the jurisdiction of the United States, this is a global issue that requires both local and global policy solutions.

Application of this Research

I have already presented initial findings to resource managers on the ground at Pihemanu. I will also present my findings and management suggestions at an upcoming albatross team meeting at the US Fish and Wildlife Service in June 2022. This paper and the comprehensive dataset that I compiled will be made available to the US Fish and Wildlife Service, and will be used to inform an update to the Mōlī species status assessment in July 2022.

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MŌLĪ: MANAGEMENT SUGGESTIONS

HEAT STRESS

- *Cost/benefit analysis of invasive tree removal*
- *Implementation of shade structures that allow for airflow*

FLOODING

- *Removal of as many impermeable surfaces as possible, or finding creative ways to increase permeability (i.e. drilling holes in paved surfaces)*
- *Implementation of channels to direct excess water back to ocean and away from nests*

NPGO

- *Inclusion of NPGO and other climate indices in species status assessments and projections, with understanding that the NPGO may change over time*
- *Treatment of each breeding colony as unique in its responses to climate indices and global change*

GLOBAL CLIMATE CHANGE

- *Including climate projections in species status assessments, management plans, and potential ESA listings*
- *Investment in more studies to investigate further how climate change affects sentinel species and the Pacific pelagic food web*

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