



## Using non-systematic surveys to investigate effects of regional climate variability on Australasian gannets in the Hauraki Gulf, New Zealand <sup>☆</sup>



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### ABSTRACT

Few studies have investigated regional and natural climate variability on seabird populations using ocean reanalysis datasets (e.g. Simple Ocean Data Assimilation (SODA)) that integrate atmospheric information to supplement ocean observations and provide improved estimates of ocean conditions. Herein we use a non-systematic dataset on Australasian gannets (*Morus serrator*) from 2001 to 2009 to identify potential connections between Gannet Sightings Per Unit Effort (GSPUE) and climate and oceanographic variability in a region of known importance for breeding seabirds, the Hauraki Gulf (HG), New Zealand. While no statistically significant relationships between GSPUE and global climate indices were determined, there was a significant correlation between GSPUE and regional SST anomaly for HG. Also, there appears to be a strong link between global climate indices and regional climate in the HG. Further, based on cross-correlation function coefficients and lagged multiple regression models, we identified potential leading and lagging climate variables, and climate variables but with limited predictive capacity in forecasting future GSPUE. Despite significant inter-annual variability and marginally cooler SSTs since 2001, gannet sightings appear to be increasing. We hypothesize that at present underlying physical changes in the marine ecosystem may be insufficient to affect supply of preferred gannet main prey (pilchard *Sardinops* spp.), which tolerate a wide thermal range. Our study showcases the potential scientific value of lengthy non-systematic data streams and when designed properly (i.e., contain abundance, flock size, and spatial data), can yield useful information in climate impact studies on seabirds and other marine fauna. Such information can be invaluable for enhancing conservation measures for protected species in fiscally constrained research environments.

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### 1. Introduction

Many studies have explored quantitative and qualitative relationships between ecosystem state and seabird vital rates and life history parameters within the context of climate change impacts (Ainley and Blight, 2009; Chambers et al., 2011; Dann et al., 2003; Mills et al., 2008), predominantly natural climatic fluctuations. Seabirds are subject to the vagaries of both terrestrial and oceanic changes as they breed on

land but spend the majority of their lives at sea (Lack, 1968). These long-lived marine apex predators are well known “biomonitor species”, offering opportunities to detect and assess the biological effects of changes in physical parameters (sea surface temperature – SST, salinity, depth of thermocline and environmental oscillations) of the marine ecosystem (Furness and Camphuysen, 1997; Schreiber and Schreiber, 1984).

To date, research into climate impacts on marine ecosystems tends to focus on biogeochemical and lower trophic effects (Doney et al., 2012; Ito et al., 2010). However, this is changing with recent studies now involving an understanding climate variability effects on top marine predators, as reviewed in Hobday et al. (2013) and ecosystem forecasting and downscaled modelling in fisheries ecology (Hollowed et al., 2013). There is also a wealth of literature on climate impacts on seabird reproductive biology and population characteristics (reviewed in Sydeman et al., 2012), although, studies in waters around Australia

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and New Zealand in the south-western Pacific are limited (Chambers et al., 2011).

Previous studies on seabirds indicate that they adapt variably to climate change – the effects are often dictated by intrinsic life history factors and indirectly, through increases or decreases in SST and other climatological factors (Chambers et al., 2012, 2013; Quillfeldt and Masello, 2013). Although seabird responses to environmental change are difficult to predict, there are certain consistent patterns (e.g. changes in distribution, phenology) that do enhance our ability to understand and forecast potential population level consequences in different geographic regions.

The need for inter-decadal time series data has created impetus to establish target species or ecosystem-specific studies. However, such studies are not always possible with depreciating research capacity and budgets worldwide. Thus, alternative data sources need to be considered while acknowledging the limitations associated with these datasets.

Information gleaned from examining historic and current climate trends and purported correlation with species distribution or occurrence patterns, and other demographic parameters can help shape

how future studies involving systematic and non-systematic data collection are structured and what parameters are influential. This is especially true for mobile species such as seabirds (Bunce et al., 2002) and marine mammals (Ballance et al., 2006) that feed at the top of the food chain, but are part of a complex food network that generally preclude direct correlations with physical and biological changes. However, they can respond to some systemic changes more strongly than others.

We consider a survey to be systematic if data was collected from a randomized study design with an equal probability of sampling all points in the study area, e.g., line-transect boat or aerial surveys (Buckland et al., 2012). Whereas, we consider non-systematic surveys to be data collected opportunistically from a boat or aircraft providing a reasonable coverage of the study area and similar methods of data collection.

The Hauraki Gulf (HG) North Island, New Zealand (Fig. 1) is recognized for its cultural, economic and ecological significance as a Marine Park (Hauraki Gulf Marine Park Act (2000), Parliamentary Counsel Office, Wellington, New Zealand). The HG, which encompasses an area of ca. 4000 sq km, is a shallow (maximum water depth ~60 m), semi-enclosed body of water riddled with islands and shallow reefs that

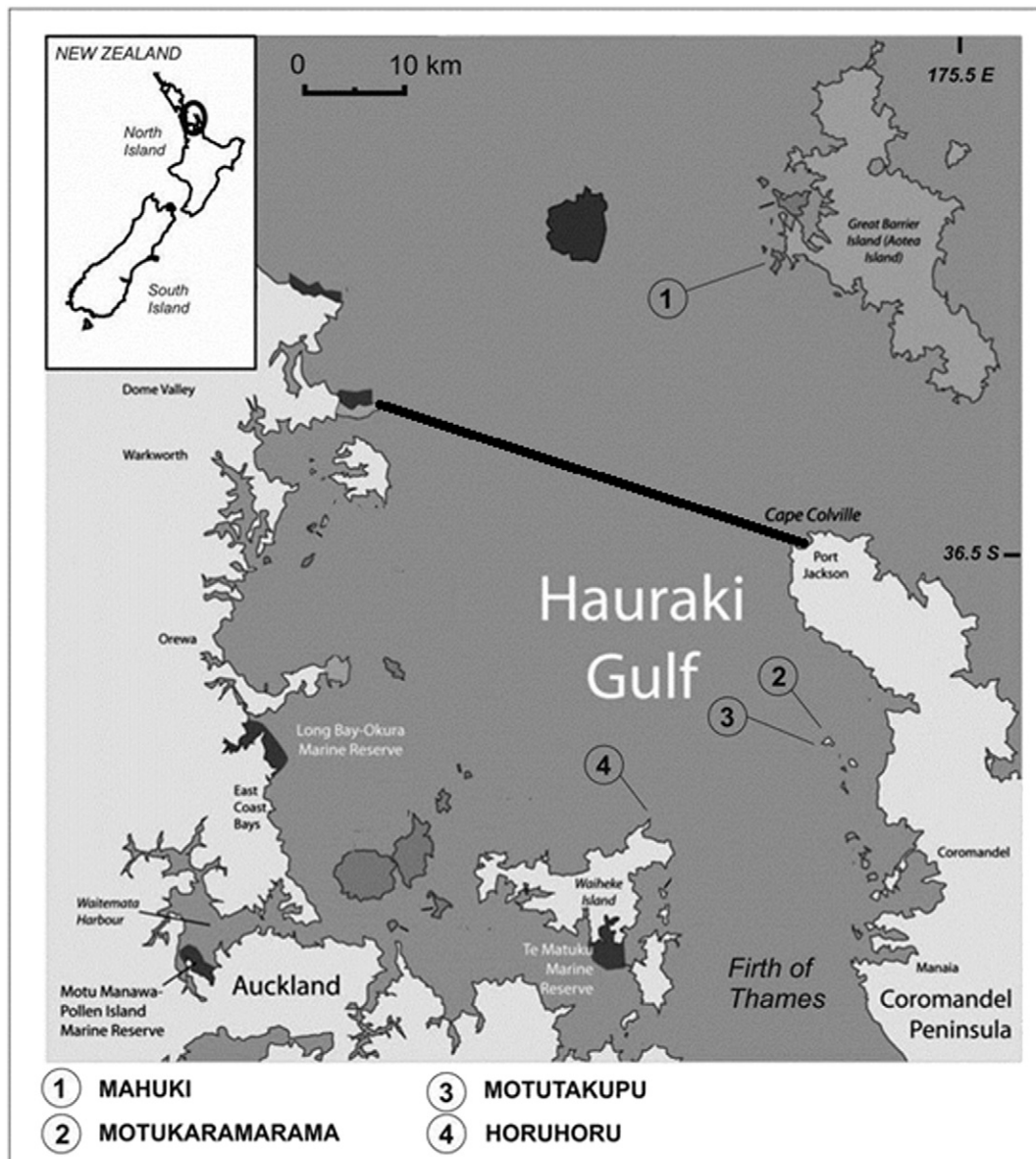


Fig. 1. Study area and location of the main gannet colonies in the HG (New Zealand). The solid black line indicates the boundary line between inner and outer Hauraki Gulf.

extend into waters of the western Pacific Ocean. Water circulation in the region is primarily driven by tides and wind (Gaskin and Rayner, 2013; Heath, 1985; Zeldis et al., 2004). Most of the HG area is also recognized as an ‘Important Bird Area’ (IBA) by New Zealand Forest and Bird (<http://www.forestandbird.org.nz/>), an affiliate of Birdlife International (Gaskin and Rayner, 2013).

This region is a breeding area for one of the most successful seabirds in New Zealand, the Australasian gannet (*Morus serrator*; hereafter gannets). Gannets feed mainly on pelagic fish and squid (Machovsky-Capuska et al., 2011a; Robertson, 1992; Schuckard et al., 2012; Tait et al., 2014). These highly specialized marine predators have been reported to travel for food as far as 388.5 km (Machovsky-Capuska et al., 2013a, 2014) with the ability to assess prey density to increase foraging success (Machovsky-Capuska et al., 2013b). Their populations have been increasing since the 1980s around New Zealand and the 1990s in Australia (Bunce et al., 2002). Currently, there are 29 gannet colonies in New Zealand, three located on the east coast and 26 on the west coast, with an estimated total of 48,509 pairs based on a census in 2000 (Nelson, 2005), and an annual mean population growth rate of 2.3% (Robertson, 1992).

The HG is home to four breeding colonies: Horuhoru Island, Mahuki Island, Motukaramarama, and Motutakupu (Wingham, 1985, 1989), with an estimated population of 12,726 pairs according to the 1980/81 census (Wodzicki et al., 1984) – no recent counts are available. It appears that gannet populations may be robust in the HG; however, with increasing human impacts and changing oceanographic conditions, it is unknown how these changes are permeating into the ecosystem and affecting gannet populations (Gaskin and Rayner, 2013). For example, the HG supports a highly profitable fishery for snapper (*Pagrus* spp.), as well as marine farming. In fact, New Zealand’s largest marine farms are in Firth of Thames, located in the southern sector of the HG (Aquaculture New Zealand, 2010).

Increases in gannet populations off New Zealand and Australia have been attributed to warming SST, increased El Niño Southern Oscillation (ENSO) activity and associated with increased (preferred) prey availability, i.e. pilchard (*Sardinops sagax*) (Bunce et al., 2002). The effect of expanding inshore commercial fishing activity in New Zealand leading to a greater presence of surface-schooling fish, normally preyed on by commercial species, may also impact gannet foraging behavior (Robertson, 1992; Schuckard et al., 2012). However, such overlap with commercial fisheries also raises the risk of gannet mortality via gear entanglements (Norman, 2000).

In this study, we use a dataset collected during non-systematic surveys, to explore potential linkages between regional and global climate variability and observed inter-annual fluctuations in gannet sightings in the HG. Specifically, we examine how regional variability correlates with global climate processes (e.g. ENSO), and with gannet sightings. In addition, we provide preliminary results about leading and lagging climate variables and climate predictor variables that could potentially influence gannet populations in the HG. This study showcases the potential scientific value that non-systematic long-term datasets can provide, if appropriately employed, to fill regional data gaps in resource constrained settings.

## 2. Methods

To examine relationships between 9-year observations of gannets in the HG, New Zealand (36.3°S, 175.08°E) and regional oceanographic and climate variables, we used the Simple Ocean Data Assimilation (SODA) reanalysis product (Version 2.0.2-4) (Carton et al., 2000a,b; Tillinger and Gordon, 2010). We acquired total and anomaly data (i.e. departure of observed conditions from average conditions in that region) for the following variables from 1990 to 2012: monthly and annual SST, zonal (west–east) and meridional (south–north) wind stress (horizontal force of the wind at the surface of the ocean) and velocity,

and cube of wind speed (a measure of water turbulence and mixing in surface waters).

The SODA analysis is derived from the global circulation model that uses the Geophysical Fluid Dynamics Laboratory Modular Ocean Model (Version 2.b) (Carton et al., 2000a,b). Data is derived over a rectangular grid covering our region of interest (i.e. HG). SODA data are stored on a  $0.5 \times 0.5^\circ$  grid with a resolution at  $36^\circ\text{S}$  to be approximately 44 km by 55 km. The chlorophyll data was obtained from NASA’s MODIS mapped, ‘monthly’ data on  $9 \text{ km}$  or  $1/12^\circ$  global grid (<http://oceandata.sci.gsfc.nasa.gov/>), available from 2003 to 2012 for the HG.

Gannet data were collected across all austral seasons between 2001 and 2009 on board *Dolphin Explorer* (DE), a 20 m tour catamaran powered by twin 350 horse-power inboard diesel engines, with a 5 m elevated observation platform. Due to permit conditions, tours conducted by DE in the Hauraki Gulf were restricted to waters south of a line from Cape Rodney to Great Barrier Island and to Cape Coleville on the Coromandel Peninsula (Fig. 1); and in water depths  $>10 \text{ m}$ . Data presented here represent all months of each year with the exception of August–September 2002 and January–May 2007, when the vessel was on dry dock. While surveys were non-systematic, survey routes selected were based on prevailing weather and sea conditions, with an attempt made to cover regions not previously surveyed within that month in order to facilitate on-board research focusing on common dolphin (*Delphinus* sp., Stockin et al., 2008b, 2009) and Bryde’s whales (*Balaenoptera edeni*, Wiseman et al., 2011).

Observations were undertaken by experienced observers using a continuous scan sampling methodology (Hoffman et al., 1981) visually with or without binoculars (Bushnell  $10 \times 50$  magnifications). Sighting cues used to detect cetaceans included splashing and/or water disturbance due to activity of animals, including gannets. Once within 400 m of a group of gannets and other seabirds, environmental variables were recorded (water depth, SST, tidal and sea state, visibility, wind direction and speed). Time and location of gannet sightings were noted using a Global Positioning System (GPS). Data included in the analysis were limited to good visibility ( $\geq 1 \text{ km}$ ) and Beaufort Sea State  $<4$ .

Gannet sighting data were analyzed for 2001 to 2009 (Fig. 2) and included data for 99 months. The number of individual gannets observed per sighting or flock size was not recorded. To normalize sightings information across months and years, a sighting per unit effort was calculated, where:

Gannet Sightings Per Unit Effort (GSPUE)

$$= (\text{Number of Gannet observations}) / (\text{Number of trips per month}).$$

We used monthly GSPUE to correlate with mean monthly climate and oceanographic SODA variables across years (2001–2009). Gannets are commonly found in multi-species foraging aggregations. These

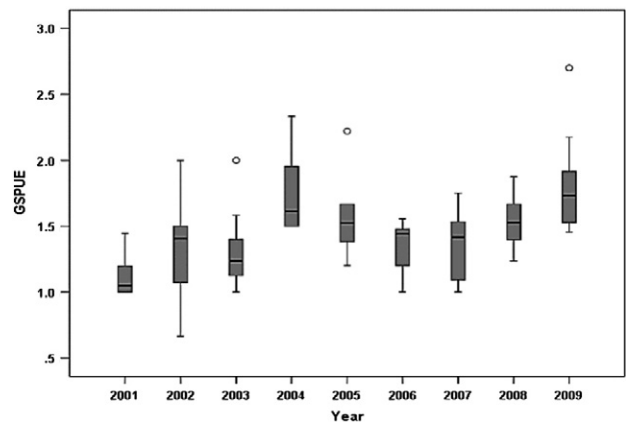


Fig. 2. Gannet Sightings Per Unit Effort (GSPUE) from 2001–2009 calculated from surveys conducted from a platform of opportunity in HG, New Zealand.



aggregations can include common dolphins, Bryde's whales, shearwaters and terns, kahawai (*Arripis* spp.), jack mackerel (*Trachurus* spp.), snapper (*Pagrus* spp.) and hammerhead sharks (*Sphyrna* spp.). The frequency of occurrence of these multispecies associations is reflective of prey abundance (Stockin et al., 2008a,b, 2009; Machovsky-Capuska et al., 2011a). As such, we calculated an annual Multi-species SPUE (MSPUE), which is the occurrence of multi-species aggregations during gannet sightings and correlated the MSPUE with annual mean climate and oceanographic SODA parameters for HG.

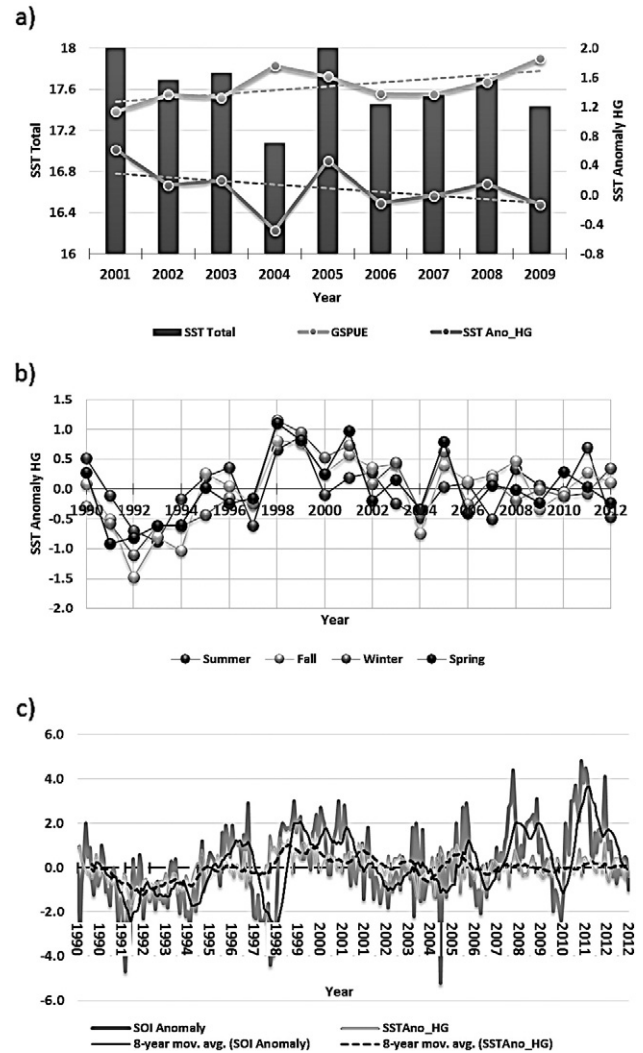
To explore the influence of global climate processes via teleconnections on regional climate dynamics, we investigated ENSO and regional SST pattern correlations over a longer time series (1990–2012). We used Southern Oscillation Index (SOI) total and anomaly data from the Bureau of Meteorology, Australia (<http://www.bom.gov.au/climate/>), and Niño 3.4 (equatorial Pacific 170 W–120W, 5 S–5N) and Niño 4 (equatorial and central Pacific 160 E–150 W, 5 S–5 N) region data, available through the Climate Prediction Centre, National Centers for Environmental Prediction, USA (NCEP; <http://www.cpc.ncep.noaa.gov/data/>). These “Niño boxes” are typically used in the diagnosis and forecast of El Niño.

We also examined a potential association with the Southern Annular Mode (SAM) or Antarctic Oscillation, which is the westerly wind belt around Antarctica with strong influence on large-scale variability in atmospheric circulation in the Southern Hemisphere and describes large-scale alternations of atmospheric mass between the mid- and high latitudes. Typically, negative SAM is associated with El Niño events (Wang and Cai, 2013). On a shorter time-scale (2001–2009), we also tested for correlations between GSPUE (2001–2009) data with the global climate indices. We then conducted sample cross-correlations and ordinary linear lagged regressions of the climate and gannet time series data in R (R Core Team, 2014), to identify significant linear relationships between our time series of interest, and identify potential climate variables that might be useful predictors of GSPUE. We used a complete case analysis to deal with GSPUE missing values ( $n = 9$ ). The time series were examined for significant evidence of non-zero correlations for lags 1–20 months using the Ljung–Box test in R. Climate data were lagged by one month and tested against GSPUE data (2001–2009). Maximum lags ( $k$ ) were automatically limited to one less than the number of observations in the series, but were also evaluated based on cross-correlation function (CCF) lag plots. Since we were primarily interested in identifying “leading” climate variables to help predict future values of GSPUE, we focused on the negative  $k$  spectrum.

### 3. Results

We ran parametric tests as data were normally distributed with constant variance. The GSPUE was significantly different across years (ANOVA,  $F = 7.580$ ,  $n = 99$ ,  $df = 8$ ,  $P < 0.0001$ ), but not across months within each year (ANOVA,  $F = 0.651$ ,  $n = 99$ ,  $df = 11$ ,  $P = 0.781$ ,  $\alpha = 0.05$ ). In general, an increase in gannet observations corresponded to an overall decrease in HG annual mean SST (total) from ca. 18.2 to 17.4 °C (Fig. 3a). Although the mean annual SST has remained stable, ranging from 17.5 °C in 1990 to 17.7 °C in 2012, seasonal SST anomalies in HG indicate an overall cooler period in the 1990s, with a slightly warmer period after 1998, followed by a decline and plateau (Fig. 3b). This trend is also reflected in the overall variability in SST anomaly in the HG since 1990, which is negatively correlated with SOI Anomaly (Fig. 3c).

Pearson's correlations of GSPUE and SODA climate and oceanographic variables resulted in a significant correlation with only SST anomaly (Pearson's correlation  $r = -0.226$ ,  $n = 99$ ,  $p < 0.05$ ). Annual correlations between MSPUE and all annually averaged SODA variables were statistically non-significant. For wind velocities and stress, values greater than zero indicate northerly winds in the meridional direction (S–N) and values greater than zero indicate easterly winds in the zonal direction (W–E). Overall, during the period of interest, 3-year



**Fig. 3.** a) Gannet sightings (GSPUE (y-axis)) as a function of regional HG SODA derived mean SST (total) and SST anomaly in the HG (SST Ano\_HG); b) seasonal changes in SST Ano\_HG (1990–2012) based on SODA data; and c) trends in SOI anomaly (Source Climate Prediction Center, National Center for Environmental Prediction, USA) and SST Ano\_HG with 8-year averages from 1990–2012.

moving averages suggest that winds tended to be more north and eastwards in 2004, south and eastwards between 2005 and 2007, and north and westwards since 2007 (Fig. 4). In general, wind cube and chlorophyll anomaly data, based on 3-year moving averages, show a decrease after 2006–2007 (Fig. 4).

We found no significant correlations between GSPUE and the global climate indices. Over a longer time frame (1990–2012), there are clear and significant relationships between regional SST in the HG and all global climate indices tested. SST HGs (total and anomalies) were positively correlated with SAM and SOI and predictably, negatively correlated with Niño 3.4 and 4.0 indices (Appendix).

Niño 3.4 and SOI variability suggests that in general 2009–2010, 2006–2007, 2002–2003 were associated with weak to moderate El Niño periods and weak SOI with the strongest ENSO activity during 1997–1998 and 1994–1995. In contrast, La Niña was strong during 2010–2012 and generally moderate to weak historically for the time period considered (Source: Bureau of Meteorology, Australia “ENSO wrap up” <http://www.bom.gov.au/climate/enso/>). Generally, sustained periods of negative (positive) SOI are associated with warm (cold) ocean waters corresponding to El Niño (La Niña) episodes (Fig. 3c).

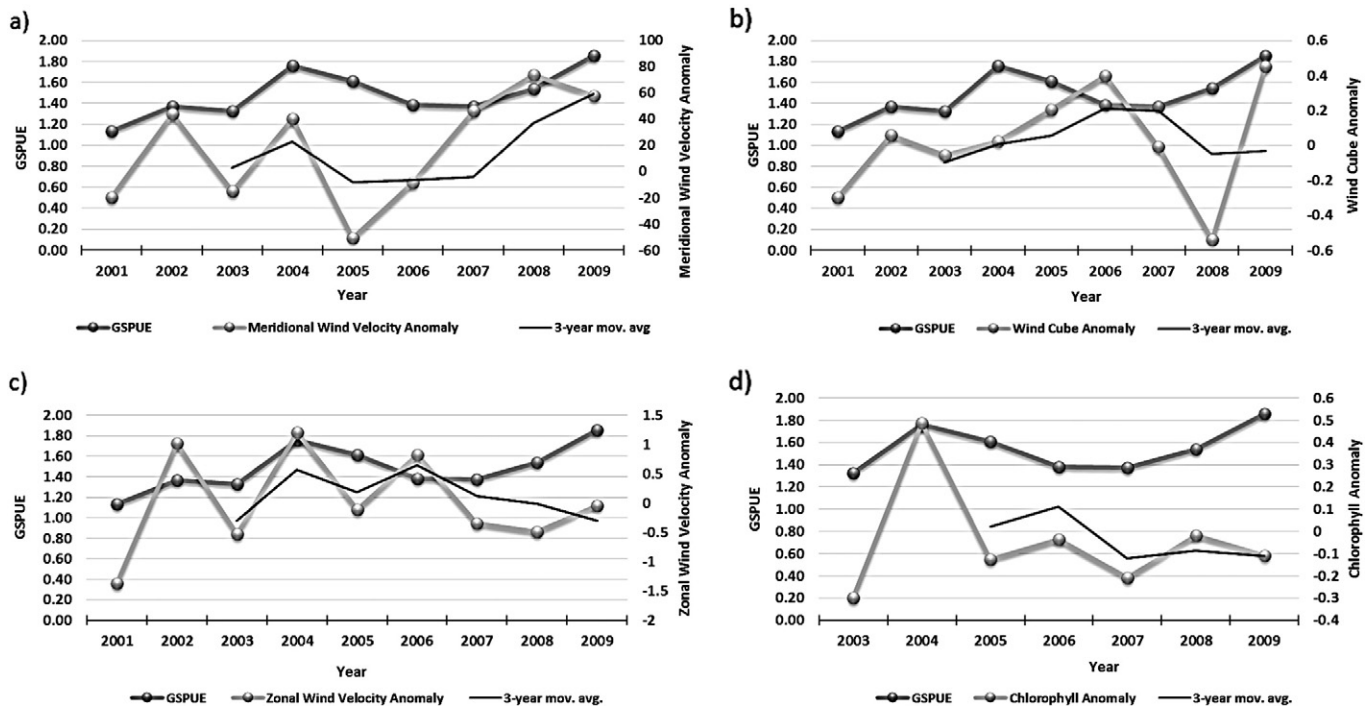


Fig. 4. Observed correlation between inter-annual variability in gannet observations from platform of opportunity data (2001–2009) represented by GSPUE (right y-axis) and anomalies (left y-axis) in regional mean climatological SODA data (2001–2009). (Note: Chlorophyll anomaly extracted from NASA MODIS available from 2003).

Since the time series satisfied the properties for a stationary series (autocorrelation for a specific lag is same throughout the time series), we conducted sample CCF and lagged regressions. For a specific lag $_{t+k}$  ( $t$  = time,  $k$  = number of lags), negative correlations tend to imply that the predictor variable ‘leads’ the dependent variable of interest, and positive values could suggest that climate variables ‘lag’ the outcome variable. For example, in Fig. 5, the negative correlations for meridional wind velocity (total and anomaly) for negative  $k$ , imply that these variables ‘lead’ GSPUE. Whereas, positive correlations of cube of wind speed (total and anomalies), SOI anomaly and SAM suggest that these could ‘lag’ GSPUE (Fig. 5). Dominant correlations corresponded to coefficients of  $\pm 0.15$  or higher depending on the variable of interest. Lags with high correlation coefficients were then tested further with lagged linear regressions (variables with significant model outputs are shown in Table 1).

Based on scatter plots of climate variable ( $x_t$ ) and their lags ( $x_{t-1}$ ) and Partial Autocorrelation Function (PACF) residuals, we determined that an autoregressive model of order 1 or AR (1) would be applicable, which is a linear association of the current value of the time series on the previous value ( $t-1$ ). Among climate variables tested meridional wind velocity model coefficients were significant for lags, 2, 8, and 14 and lag 2 and 14 based on meridional wind velocity anomaly coefficients.

Cube of wind speed total and anomaly coefficients were significant for lags 3, 7, and 9 and lags 2, 3, 7, and 9, respectively. Similarly, lag 5 and 11 for SAM and lag 2 for SOI anomaly resulted in significant coefficients (Table 1). However,  $R^2$  values were weak (ranging from 7% to a maximum of 16%, Table 1). Autocorrelation and Partial Autocorrelation Functions (ACF and PACF) of the residuals indicated minor autocorrelation.

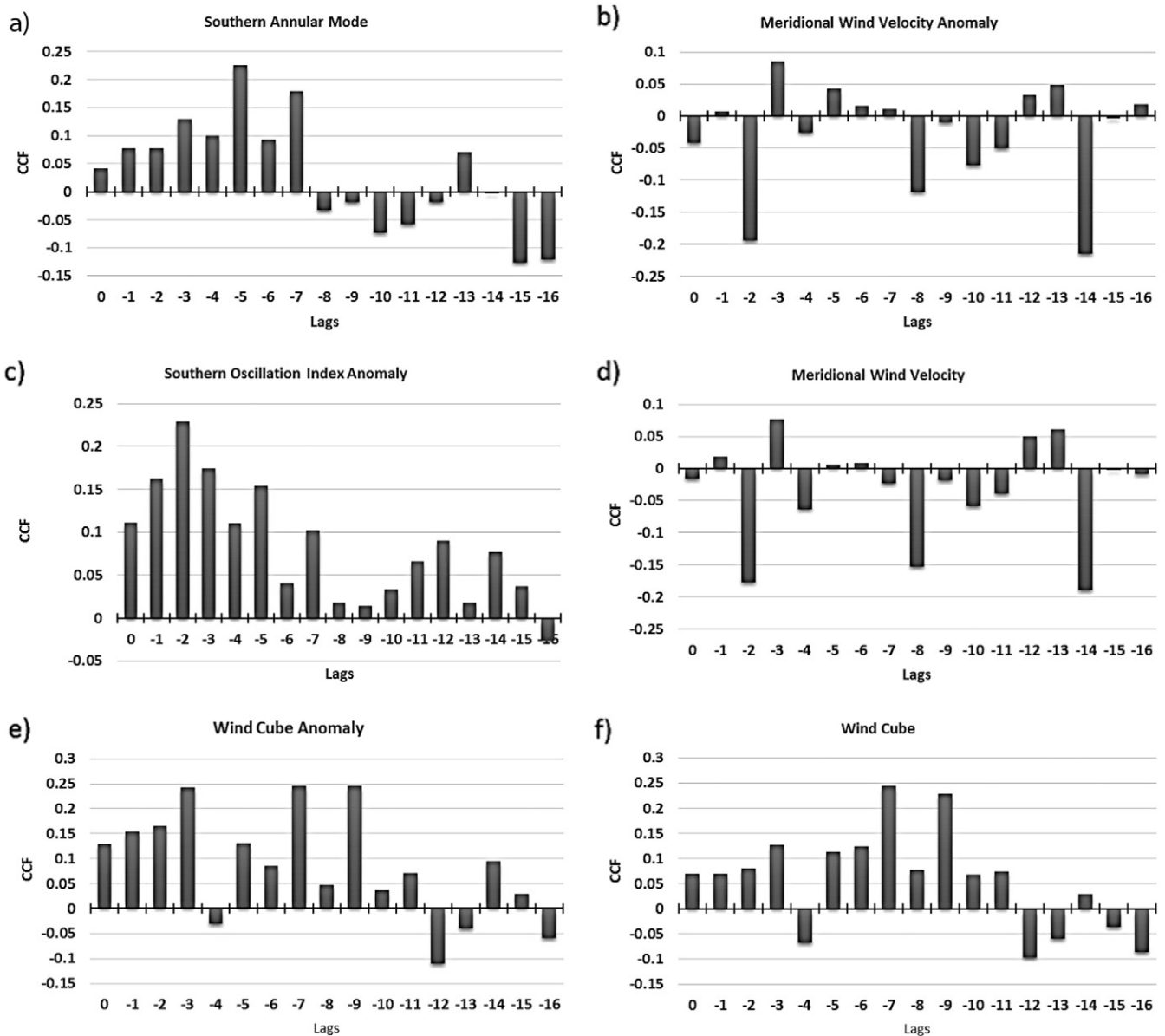
#### 4. Discussion

Changes in the ecosystem condition manifest themselves through physical changes that directly and indirectly affect trophic relationships and species abundance (Burthe et al., 2012; Mills et al., 2008; Stenseth

et al., 2002; Sydeman et al., 2012). Alteration of ocean characteristics due to anthropogenic climate change is now indisputable (IPCC, 2013), but how these fluctuations translate into impacts on marine organisms at different spatial and temporal scales is less understood (Ballance et al., 2006).

Our analysis indicates that inter-annual variability in gannet sightings was significantly and negatively correlated with SST anomaly in HG. Lack of direct correlation with other variables tested could be due to, a) our inability to detect a relationship due to data limitations, b) as flexible foragers (Schuckard et al., 2012), gannets have successfully adapted to variable climatic conditions, or c) there may be a delayed reaction to systemic changes (Doney et al., 2012). Despite the slightly cooler SSTs, we suggest that oceanographic conditions offered ideal foraging conditions for increased gannet observations during the period of study. This is supported in part by the spatial distribution of gannets in the study area with observations dominant around 36.5 and 37° S latitude consistently since 2001 (Fig. 6).

Although we did not see any significant relationship between GSPUE and global climate indices, particularly the Southern Oscillation Index – SOI as evidenced in previous works (Bunce et al., 2002; Stenseth et al., 2002), lagged regression models suggest that the cube of wind speed, meridional wind velocity, SAM, and SOI could be influential factors governing gannet patterns in HG. But since they individually explain minimal variation in gannet observations, their collective and individual predictive value requires validation. In spite of the minimum variability explained by these variables, we know from other studies, that wind speed and direction can have an effect on foraging efficiency and breeding success, e.g., wandering albatross, *Diomedea exulans*, in the Southern Ocean (Weimerskirch et al., 2012). Weimerskirch et al. (2012) found that the meridional component was a major driver for increase in flight speed during foraging trips for wandering albatross. Similarly, Amélineau et al. (2014) noted that wind force and direction could affect foraging costs in northern gannets, *M. bassanus*. In New Zealand, negative phases of the SAM are associated with increased westerlies and lighter winds during the positive phases of SAM (Renwick and Thompson, 2006). Thus, each of the predictor variables identified here



**Fig. 5.** Cross-correlation function (CCF, y-axis) lagged plots of selected climate parameters that 'lead' or 'lag' GSPUE for negative lags (x-axis, max lag = 16 months). Generally, dominant correlations of  $> \pm 0.15$  were considered for further analysis.

could have potentially important effects on foraging and breeding success for gannets, and merit further investigation.

Environmental variables can also operate in an additive fashion, constructing Generalized Additive Models (GAMs) using various climate and other (e.g. year and month) parameter combinations may help explain gannet variability. To avoid overstating results and to discount spurious correlations, we emphasize that such models should be built using robust gannet datasets and population metrics such as flock size or abundance. Opportunistic surveys, if designed to collect these additional metrics or used in combination with systematic survey data, will likely strengthen preliminary conclusions and reduce uncertainty associated with such datasets.

The strong relationships between regional SST and global climate indices found here suggests that global climate variability could affect the climate seascape of HG, but not necessarily translate into observable changes in upper-trophic predators based on current evidence. Changes in SOI can alter wind strength and direction, nutrient upwelling and SSTs (Bunce et al., 2002; Trenberth and Shea, 1987). As such in the

HG, there are seasonal shifts in wind patterns which fluctuate during El Niño and La Niña episodes such that westerlies (winds from the west) are typically associated with El Niño periods and upwelling (Broekhuizen et al., 2002). SST patterns have been steady over a 20-year period, but cooler than average in the region during the time frame of the analysis. Marginal changes in thermal regimes can have profound effects on seabird populations as evidenced in the northwest Atlantic (Montevecchi and Myers, 1997), however, it remains to be seen if gannets in HG will be affected if a cooler regime continues. In HG, similar to trends observed nationally in Australia and New Zealand (Bunce et al., 2002), gannet populations may be stable and increasing. Variable wind patterns and ENSO periods notwithstanding in HG, suggest that it is possible that food is readily available and plentiful for them to remain in the area. Nonetheless, independent and current census counts are necessary to contextualize a likely increasing trend in gannet populations in HG.

In terms of the prey field, New Zealand gannet diet is composed of pelagic fish and squid species, predominantly, pilchard (*Sardina* spp.),

**Table 1**

Lagged multiple regression model outputs wherein GSPUE is assumed to be linear function of historic lags (in months) for the following climate variables with significant coefficients: Wcube = cube of wind speed, WcubeAno = cube of wind speed anomaly, Mvel = meridional wind velocity, SOIAno = Southern Oscillation Index anomaly, and SAM = Southern Annular Mode.

| Coefficients:  | Estimate | Std. error | t value | Pr(> t ) |
|--|----------|------------|---------|----------|
| Model: GSPUE ~ Wcubelag3 + Wcubelag7 + Wcubelag9   |          |            |         |          |
| Wcubelag3  | 0.0005   | 0.0002     | 2.223   | 0.029*   |
| Wcubelag7  | 0.0005   | 0.0003     | 2.064   | 0.042*   |
| Wcubelag9  | 0.0008   | 0.0003     | 2.766   | 0.007**  |
| Multiple R-squared = 0.15, Adjusted R-squared = 0.12<br>F = 5.197 on 3 and 86 df, p = 0.002  |          |            |         |          |
| Model: GSPUE ~ WcubeAno2 + WcubeAno3 + WcubeAno7 + WcubeAno9                                 |          |            |         |          |
| WcubeAno2  | 0.0004   | 0.0003     | 1.263   | 0.210    |
| WcubeAno3  | 0.0006   | 0.0003     | 1.979   | 0.051    |
| WcubeAno7  | 0.0007   | 0.0003     | 2.255   | 0.027*   |
| WcubeAno9  | 0.0008   | 0.0003     | 2.483   | 0.015*   |
| Multiple R-squared = 0.19, Adjusted R-squared = 0.15<br>F = 4.999 on 4 and 85 df, p = 0.001  |          |            |         |          |
| Model: GSPUE ~ Mvellag2 + Mvellag8 + Mvellag14   |          |            |         |          |
| Mvellag2   | -0.070   | 0.027      | -2.583  | 0.012*   |
| Mvellag8   | -0.043   | 0.026      | -1.687  | 0.096    |
| Mvellag14  | -0.075   | 0.027      | -2.834  | 0.006**  |
| Multiple R-squared = 0.15, Adjusted R-squared = 0.12<br>F = 4.885 on 3 and 81 df, p = 0.004  |          |            |         |          |
| Model: GSPUE ~ SOIAno1 + SOIAno2 + SOIAno3 + SOIAno5   |          |            |         |          |
| SOIAno1  | 0.019    | 0.0270     | 0.710   | 0.480    |
| SOIAno2  | 0.057    | 0.0280     | 2.086   | 0.040*   |
| SOIAno3  | 0.028    | 0.0293     | 0.963   | 0.339    |
| SOIAno5  | 0.001    | 0.028      | 0.038   | 0.970    |
| Multiple R-squared = 0.12, Adjusted R-squared = 0.08<br>F = 3.108 on 4 and 89 df, p = 0.019  |          |            |         |          |
| Model: GSPUE ~ SAMlag5 + SAMlag7   |          |            |         |          |
| SAMlag5  | 0.071    | 0.035      | 2.048   | 0.044*   |
| SAMlag7  | 0.060    | 0.036      | 1.669   | 0.099    |
| Multiple R-squared = 0.09, Adjusted R-squared = .07<br>F = 4.172 on 2 and 89 df, p = 0.019   |          |            |         |          |
| Model: GSPUE ~ MvelAno2 + MvelAno14  |          |            |         |          |
| MvelAno2   | -0.092   | 0.029      | -3.258  | 0.002**  |
| MvelAno14  | -0.097   | 0.028      | -3.527  | 0.001*** |
| Multiple R-squared = 0.17, Adjusted R-squared = 0.16<br>F = 8.835 on 2 and 82 df, p = 0.0003 |          |            |         |          |

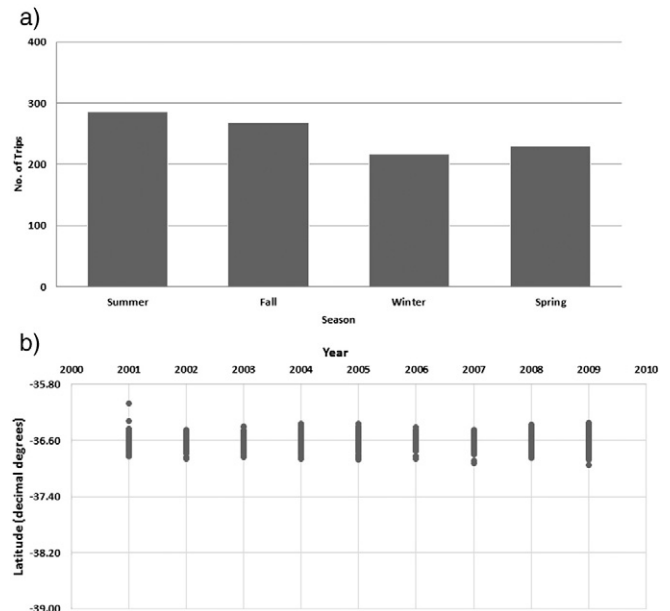
\*\*\* 0.001.

\*\* 0.01.

\* 0.05.

anchovy (*Engraulis* spp.), saury (*Scomberesox* spp.), jack mackerel, squid (*Nototodarus* spp.) and garfish (*Belone* spp.) (Wingham, 1985, 1989; Robertson, 1992; Machovsky-Capuska et al., 2011a,b; Schuckard et al., 2012, Tait et al., 2014). Anchovies are abundant throughout the Hauraki Gulf during spring and migrate seaward in winter (Paulin et al., 1989, Kendrick and Francis, 2002). Peak abundance occurs in winter with high productivity leading to large schools of anchovies often closely associated with pilchards, which are abundant during warmer, less productive periods (Lecomte et al., 2004).

Pilchards are susceptible to viral disease and are sensitive to climatically driven oceanographic conditions (Paul et al., 2001; Whittington et al., 1997). Nonetheless, pilchards accounted for more than 50% of the diet of gannets at Port Phillip Bay between 1995 and 1998 (Bunce et al., 2002), 90% of the diet of gannets at Farewell Spit between 1995 and 2001, excluding 1996 that switched to anchovy due to a mass pilchard mortality (Schuckard et al., 2012), and were the most abundant prey species found in the diet of gannets in the HG between 1979 and



**Fig. 6.** a) Seasonal survey effort conducted from platform of opportunity between 2001 and 2009 in Hauraki Gulf, New Zealand. b) Annual spatial variability in gannet sightings from four boat data (2001–2009) in Hauraki Gulf, New Zealand.

1980 (Robertson, 1992; Wingham, 1985). The absence of pilchards as a primary food source is attributed to be a major factor for the biggest crash in gannet populations ever recorded in New Zealand including at the Farewell Spit colony where hundreds of birds were found dead in 1996 (Schuckard et al., 2012).

Pilchards (also known as sardines) have a preference for warm waters (Chavez et al., 2003; Neumann, 2001), but remain tolerant to a wide range of temperatures, with spawning occurring between 13.5 and 25 °C as determined in Pacific sardines (Lluch-Belda et al., 1992). Thus, the marginally cooler SSTs recorded in the HG region may still be optimum for pilchard spawning, although recruitment and productivity levels in these waters are unknown. The East Auckland Current and shelf upwelling, along with tidal changes drive circulation patterns and interact to affect nutrient production in the Gulf, which is further influenced by ENSO patterns and Interdecadal Pacific Oscillations (IPO) (Zeldis et al., 2004). So, lack of upwelling may have an impact on pilchard/anchovy populations, with further investigations necessary to see how prey availability is linked with gannet population fluctuations.

The advantages of opportunistic datasets are that they are continuous both in terms of effort and temporal scales particularly, commercial operations. The standalone scientific value of these datasets cannot be discounted. For example, Williams et al. (2006) demonstrated that it is possible to estimate marine mammal abundance from non-randomized opportunistic surveys and be potentially used in management decision-making. Fisheries observers on commercial fishing operations in the USA are one of the primary sources of marine mammal by-catch information, which is utilized in marine mammal stock assessments by the US National Marine Fisheries Service (<http://www.nmfs.noaa.gov/pr/sars/>). Conversely, exclusive reliance on opportunistic data can lead to erroneous conclusions about abundance and distribution patterns due to incomplete coverage of study area and selective or improper data gathering.

Nevertheless, in areas where research efforts are limited or where adequate funding is lacking, we propose that long-term non-systematic survey results, if properly collected and analyzed, can be a valuable tool to address a variety of marine conservation problems, including discerning probable effects of regional and global climate variability on living marine resources.



In the present study, our interpretation and analysis would be significantly improved by including key metrics such as abundance and presence/absence information. Synthesis studies involving analysis of multiple species and their response to climate or oceanographic change would enhance our understanding of climate impacts within ecosystems. We further need to understand the interactive effects of climate–ecosystem variables and human impacts on seabird population dynamics to be able to forecast with increased certainty population responses to climate change (Jenouvrier, 2013). Also, since seabirds are significant ecological links between the land and the sea, changes in breeding sites and gannet vital rates are important considerations. Future studies should use multiple data streams from both systematic work and non-systematic work to better understand and predict gannet responsiveness to oceanographic and climate variability at regional scales.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.seares.2015.02.004>.

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