At-sea distribution of the black petrels (*Procellaria parkinsoni*) on Great Barrier Island (Aotea Island), 2009/10: Part 1 – Environmental variables.

Elizabeth A. Bell[1], Joanna L. Sim[2], Leigh Torres[3] and Scott Schaffer[4]

[1] Wildlife Management International Limited, 35 Selmes Road, Rapaura, RD3, Blenheim 7273, New Zealand, Email:biz@wmil.co.nz

[2] Department of Conservation, Great Barrier Area Office, Port Fitzroy, Great Barrier Island, New Zealand

[3] NIWA, Greta Point, Wellington, New Zealand

[4] San Jose State University, California, USA

Abstract

This report is part of an ongoing long-term study of the black petrel, *Procellaria parkinsoni,* on Great Barrier Island (Aotea Island) that was begun in the 1995/96 breeding season. Since the 2005/06 season, 92 Lotek™ geo-locator data-loggers, 10 BASTrak™ data loggers and 9 SIRTrack™ GPS loggers have been deployed on breeding black petrels to obtain foraging information, at-sea distribution in relation to environmental variables and possible interaction with fisheries during breeding, migration to South America and return to the Mount Hobson colony; of these, 86 Lotek™, 6 BASTrak™ and 9 SIRTrack™ loggers were retrieved this season for tracking analysis. The at-sea distribution of black petrels was derived from 46 geo-locator tracks collected between December 2005 and January 2009. Habitat use and foraging range for the black petrels was highly variable and inconsistent between breeding phase and sex. Birds foraged around the northern New Zealand, particularly along the continental shelf edges or seamounts, travelling near the Chatham Rise, further north into the Pacific (towards Fiji) and to the eastern Australian coast. Black petrels spent the non-breeding phase in a relatively small region in the coastal waters off Ecuador, South America. This study demonstrates the versatility of the black petrel habitat use relative to environmental factors and that black petrels distribute themselves relative to resource availability.

*Keywords*: black petrel, *Procellaria parkinsoni*, geo-locator, GPS, data-logger, foraging, environment, Great Barrier Island (Aotea Island), New Zealand

## 1. Introduction

The black petrel, *Procellaria parkinsoni*, is a medium-sized endemic seabird which is only known to breed on Hauturu/Little Barrier Island (36°199'S 175°082'E) and Great Barrier Island (Aotea Island) (36°187'S 175°4125'E), New Zealand (Heather and Robertson 1996). The main breeding area on Great Barrier Island (Aotea Island) is around the summit of Mount Hobson (Hirakimata) (hereafter Mount Hobson). Monitoring work carried out during the 2009/10 breeding season was a continuation of the study begun in 1995/96 (Bell & Sim 1998a, b, 2000a, b, c, 2002, 2003a, b, 2005; Bell et al. 2007, 2009; Bell et al. 2011), adding to the baseline data on the Great Barrier Island black petrel population. Field work carried out in 2006/07 season was privately funded and has not been reported in the DOC publication format. The annual report for that season can be obtained from the lead author (EAB). This part of the study will build on the earlier (Bell et al 2009) tracking and foraging data.

## 2. Objectives

The main objectives of this whole study were to undertake an annual census of the black petrel population on Great Barrier Island via burrow monitoring and the banding of adults and fledglings to establish adult mortality, breeding success and recruitment, and to investigate at-sea distribution. Population monitoring aspects are covered in Bell et al (in press). This report focuses on the at-sea distribution of black petrels in relation to environmental variables.

In summary, the study objectives covered in this report were to:

- Use light geo-locator data-loggers to determine at-sea distribution of black petrels during their breeding season (incubation and chick rearing), and during migration to and residence in South America during their winter non-breeding period.
- Analyse the logger data in relation to environmental variables (sea surface temperature, depth, slope, chlorophyll *a* and sea surface height) and foraging locations.

## 3. Methods

### 3.1 Study sites

The 35 ha study area at and around the summit of Mount Hobson on Great Barrier Island (Aotea Island; Fig. 1) was monitored three times during each of the breeding seasons between 2005 and 2010. During these visits over the 5-year period, 111 breeding black petrels were selected from the study burrows (n = 393) to have SIRTrack™ GPS loggers or Lotek™ or BASTrak™ geo-locator loggers deployed over the breeding and non-breeding phases.

In addition, six black petrels breeding on or around the summit of Hauturu/Little Barrier Island were also included in the at-sea distribution study.

## 3.2 Deployment of Geo-locator and GPS data-loggers

A total of 11 geo-locator and GPS logger devices were deployed on black petrels on Great Barrier Island between December 2005 and February 2010 (Table 1).

Ethical approval for the use of all geo-locator and GPS data-loggers was given by DOC Ethics Committee (15/12/2005, AEC127; 1/12/2007, AEC162 and 4/12/2008, AEC184).

### 3.2.1 LOTEK™ Geo-locator loggers

Ninety-two LOTEK™ LAT2500 geo-locator data-loggers (Lotek Wireless, Ontario, Canada) were deployed on known breeding adult black petrels on Great Barrier Island between December 2005 and February 2010 (Bell et al. 2009; Bell et al. 2011, Table 1). The birds were chosen from study burrows within the 35-ha study area if they had been successful breeders for at least five seasons and had been in the same pair for over the same five seasons. These data-loggers were light (6 g), small (35 mm in length and 11 mm diameter) and glued to a specially designed holder, which was then attached to the bird’s leg by two cable ties. The data-loggers were attached to the bird’s leg in about a minute. Removal of the tag was by cutting the cable ties with scissors. The total instrument load (percentage of bird’s weight) is 0.86% (for a 700 g breeding bird).

These LOTEK™ data-loggers give data on position, flight time, time spent on the water, sea surface temperature, recording sea surface temperature and ambient light data every six minutes. The data was downloaded as the devices were retrieved (between January 2006 and March 2010) and analysed using an algorithm program developed in the USA (Shaffer et al 2005).

Tracks from 40 black petrels from Great Barrier Island and 6 from Hauturu/Little Barrier Island have been processed and analysed for this report (Table 2). Additional tracks from Great Barrier Island birds (n = 45) and data will be compared in the future.

### 3.2.2 BASTrak™ geo-locator loggers

Ten BASTrak™ geo-locator data-loggers (British Antarctic Survey, Natural Environment Research Council, Cambridge, United Kingdom) were deployed in December 2008 (Table 1). As for the other data-loggers, birds were chosen from study burrows with the 35-ha study area if they had been successful breeders for at least five seasons and had been in the same pair for over the same five seasons. The BASTrak™ data-loggers measured 15 mm by 10 mm and weighed 1.5 g. These loggers were attached by cable tie to the metal band already on the bird's leg. The attachment required no adhesive and was attached in about a minute. The total instrument load (percentage of bird's weight) is 0.43% (for a 700 g breeding bird). These data-loggers give data on position, flight time and light, recording temperature and light data every six minutes. The data was downloaded as the devices were retrieved (between December 2009 and March 2010) and are currently being analysed using a filtering program developed in the UK (Richard Phillips, BAS, Cambridge, pers. comm. 2010).

### 3.2.3 SIRTrack™ GPS data-loggers

Nine Sirtrack MicroGPS™ data-loggers (Sirtrack Wildlife Tracking Solutions, Havelock North, New Zealand) were deployed between December 2008 and February 2010 (Table 1). As for the other loggers, birds were chosen from the study burrows within the 35-ha study site if they had been successful breeders for at least five seasons and had been in the same pair for over the same five seasons. The Sirtrack MicroGPS™ data-loggers were 21 g units that measured 45 mm x 25 mm x 18 mm. These data-loggers were attached to feathers in the central dorsal area using Tesa™ tape (following the successful trial during the 2001/02 and 2002/03 breeding seasons, Bell & Sim 2003a, b). When the birds were recaptured, the unit was removed by snipping the tape with scissors. Application and removal of each GPS data-logger took no longer than five minutes. The total instrument load (percentage of bird's weight) is 3.1% (for a 700 g breeding bird). These loggers give accurate position location (to within 1 m, depending on satellite reception). The loggers' recorded position data every 12 hours.

## 3.3 Analysis of tracks from geolocator devices

Light-based (Lotek™) geolocator (GLS) data were filtered by sea surface temperature (SST) and speed (see 3.3.1) to remove large location errors in data points (i.e. each GLS point has an estimated location error of ±200 km). These filtered points were then classed by breeding phase (see 3.3.2, Table 3). The GLS telemetry data from each breeding phase were than analysed in relation to the environmental variables depth, slope, sea surface temperature (SST), chlorophyll *a*, and sea surface height (SSH). Habitat use variability was compared across breeding phase and sex. Detailed plots of each flight were mapped onto New Zealand bathymetry maps. Positional data and kernel density plots from the tracks identified areas of high use by black petrels (for all birds as well as separate sexes and within different stages of the breeding cycle) within the New Zealand EEZ.

### 3.3.1 Track filtering

Data from the GLS tags were processed by algorithms developed by Shaffer et al. (2005) that incorporate threshold light techniques to determine longitude and SST to determine latitude. In temperate regions these methods are proven to reduce geolocation position errors to 202±171 km (Shaffer *et al.* 2005). However, due to less distinct SST gradients in tropical regions these methods are less successful at determining latitude. Initial plotting of the black petrel GLS tracks processed using SST to determine latitude illustrated 15 tracks that migrated east to spend the non-breeding season in the tropical waters off northern South America. These tracks had great position variability and appeared unrealistic (Fig. 2). Therefore, a speed filter was generated to step through each GLS track, point by point, to determine if the light-based latitude or SST-based latitude, or neither (skip point), were most accurate.

Code was written in Matlab® (Version 7.6, R2008a, The MathWorks, Inc.) to step through each track and assess the speed between each point, calculated as the distance to the next point (km day$^{-1}$), using both the SST derived latitude and the light-based latitude. The 'best' latitude value was selected based on the speed of the point and its location. Two different 'maximum distance' settings were incorporated into the filter: a smaller distance of 400 km day$^{-1}$ was applied when the bird was on foraging grounds. Foraging grounds were defined as west of 170°W (breeding grounds) and east of 100°W (non-breeding grounds). A larger 'maximum distance' value of 1200 km day$^{-1}$ was applied between 170°W and 100°W, when the bird was migrating. It is assumed that while on foraging grounds individuals travel more slowly because more time is dedicated to searching for prey than while migrating quickly across ocean basins. The maximum distance travelled per day while on breeding grounds was based on high-resolution GPS tracking of black petrels from GBI during the breeding season that documented a mean distance travelled per day of 195 km (±35 km) (Freeman et al 2010). Due to the estimated position error of GLS locations, 200 km was added to 195 km and rounded up to 400 km $day^{-1}$. The maximum distance travelled per day during migrations was determined based on the mean fast peak speed reported by Freeman et al (2010) of 10.20 $ms^{-1}$ (converted to 36 km $h^{-1}$ or 881 km $day^{-1}$). Additionally, Phillips et al (2006) used speeds ≥ 35 km $h^{-1}$ sustained over a 48 hr period as a threshold of unrealistic flight speeds for white-chinned petrels (*Procellaria aequinoctialis*), a similar species to black petrels. An additional 100 km was added to the GLS position error of 200 km to compensate for unexpectedly high travel speeds across the Pacific Ocean basin (i.e. due to directed flight, tail winds, etc.). Therefore, 300 km was added to 881 km $day^{-1}$ and rounded up for a maximum distance of 1200 km $day^{-1}$ during migration periods.

In the filtering process, if the derived speed of the GLS point was above the 'maximum distance' using both the SST-based and light-based latitude values, the point was skipped and the code moved on to the next point. If both SST-based and light-based latitudes generated distance values below the 'maximum distance', and the GLS point was south of 20°S, the SST-based latitude was selected. Below 20°S SST gradients are prominent and therefore SST-based latitudes are likely to be more accurate than light-based latitudes. If the GLS point was north of 20°S, the latitude that generated the smallest distance value was selected. This process also removed any position errors in light-based latitudes caused by the equinox. This filtering method was implemented on all black petrel GLS tracks and substantially reduced spatial error in locations and produced more realistic tracks (Fig. 2). Table 2 describes details of each track including the number of points used in subsequent habitat analyses after the filtering process.

#### 3.3.2 Breeding phase classification

After filtering, GLS points within each track were classed by breeding phase based on date and location. Each point along a track was assigned to one breeding phase. Breeding phase was initially based on known dates of breeding cycles of black petrels (Imber 1987, Table 3) and then refined based on location and behaviour of track points. To refine breeding phase classifications, each track was plotted and inspected to determine when the bird departed on eastward or westward migrations and when the bird arrived on foraging grounds. Migrations were characterized as directed flight east/west from the breeding or non-breeding foraging grounds. Breeding foraging grounds were defined as west of -175°W and non-breeding foraging grounds were defined as east of 100°W. Table 4 summarises the number of points classified into each breeding phase and the bounding dates of these points. Bounding dates of points in breeding phases are different than accepted dates of black petrel breeding phases (Table 3) because some tracked birds were failed breeders and therefore departed for non-breeding grounds earlier than successful breeders. Additionally, birds departed the non-breeding grounds at different times to return to breeding grounds in New Zealand.

#### 3.3.3 Distribution analyses

All GLS points within each breeding phase were merged into one file and used to create kernel density maps to describe core distribution patterns. Density contours of 95%, 75% and 50% use were generated using the Animal Movement extension in ArcView GIS (V3.2, Environmental Systems Research Institute, Inc.) to describe distribution patterns. Kernel density maps were created using a search radius of 200 km, a cell size of 25 km, and an Albers equal area conic projection. For each breeding phase three kernel density maps were generated: using all GLS points, only male GLS points, and only female GLS points.

### 3.3.4 Habitat use analysis

Habitat use patterns between and within breeding phases were compared by sampling environmental layers with GLS points within the 50% and 95% contours and comparing trends. Depth and slope values were sampled from The General Bathymetric Chart of the Oceans (GEBCO_08) grid. Slope was derived from this grid using the slope function in ArcGIS (V9.3, Environmental Systems Research Institute, Inc.). Median values of depth and slope within a 200 km radius of each GLS point were used in analyses. Matlab routines, called xtractomatic (http://coastwatch.pfel.noaa.gov/xtracto/), provided by The Coastwatch group of the National Oceanographic and Atmospheric Administration, were implemented to sample environmental data from remotely sensed satellite images at all GLS points. Median values across a 1° longitude X 2° latitude search box (i.e. accepted error for GLS data; Phillips et al 2004, Shaffer et al 2006) at each GLS location and time were obtained for the following environmental layers: SST from 5-day blended composite images, chlorophyll *a* from SeaWifs 8-day composite images, and SSH from AVISO 1-day images (for more details on sample data layers visit http://oceanwatch.pfeg.noaa.gov:8081/thredds/catalog.html). SSH data demarcate currents because warm water is less dense than cold water, so the warm water tends to be higher than cold water. SSH is used to assess the distribution of birds in relation to the location of currents and eddies. All points over land or where cloud cover prevented accurate measurements (satellite data), received a value of an undefined point (i.e. 'not-a-number, NaN; Table 4).

Habitat use patterns relative to environmental variability were analysed across breeding phases and sex through box-plots and analysis of variance (ANOVA) tests. The migration phases east and west were not included in these analyses. Habitat selection within breeding stages was determined through comparisons of environmental characteristics between GLS points within the 50% and 95% density contours. Differences and similarities in habitat use patterns between breeding phases and sex were assessed through comparisons of GLS points within the 50% density contours. Multi-co-linearity between environmental variables within in each breeding phases was assessed by calculating Spearman's rank correlation. If a correlation of 0.75 or greater was detected, one environmental variable was removed and the test was performed, then the other variable was removed and the test was re-run. Differences in results were then assessed.

# 4 Results

## 4.1 Geo-locator and GPS loggers deployment

There were 92 deployments of LOTEK™ data-loggers, 10 BASTrak™ data-loggers and 9 SIRTrack™ GPS loggers between December 2005 and February 2010 (Table 1). There were a total of 111 deployments between 2005/06 and 2009/10, of which ten devices still have to be retrieved (four BASTrak™ loggers and six LOTEK™ loggers, Table 1). Four birds that had devices deployed were recaptured, but had lost their devices at sea (two LOTEK™, one BASTrak™ and one SIRTrack™, Table 1).

Of the LOTEK™ data-loggers deployed, 49 were placed on known males, 23 were placed on known females and 20 were placed birds of unknown sex from 79 burrows (Table 1). Of the BASTrak™ data-loggers, nine were placed on known males and one on a known female from nine burrows (Table 1). Of the SIRTrack™ GPS loggers deployed, five were placed on known males, two on known females and two on birds of unknown sex from nine burrows (Table 1).

The SIRTrack™ devices only recorded one track; the remaining devices had not collected enough satellites to obtain an accurate position. The single track from the 2007/08 breeding season showed a foraging trip to East Cape.

The birds came from 97 different burrows (Table 1) and showed no adverse affects from carrying the devices. From these burrows, in all, but one season (2007/08), breeding success was similar or higher than in the study burrows as a whole (Table 1), with most successfully fledging chicks.

Devices were worn for between 12 and 421 days (Table 1) and the birds showed few, if any, adverse affects from carrying the devices. Of the birds that carried Lotek™ devices for over a year, nearly half (8 out of 18, 44%) had moderate to serious levels of rubbing abrasions and/or swellings on the legs; but this did not appear to affect either breeding success or the use of the leg. The remaining birds had little, to no damage to the legs.

Thirteen LOTEK™ geolocator loggers deployed in the 2007/08 breeding season and 2008/09 breeding season were affected by battery failure (M. Vandentillaart, Lotek Wireless, pers. comm. 7/1/09, Table 5). Six devices deployed in December 2007 stopped recording data between January and October 2008, two devices deployed in January 2008 failed in February and June 2008, two devices deployed in December 2008 did not record pass the end of December 2008 and three devices deployed in December 2008 did not record any tracks (Table 5). The remaining data-loggers had reliable tracks (Table 5).

## 4.2 Distribution patterns

As expected, distribution patterns varied by breeding phase (Figs. 3-9). The 95% contours during Incubation 2005/06 and incubation 2007/08 are similar for all, male and female points (Figs. 3 & 4). Distribution stretches across the Tasman Sea to the Australian coast and east to 160°W (Incubation 2007/08) and 170°W (Incubation 2005/06). However, the 50% contour centres over the Hauraki Gulf for all density plots except females during Incubation 2007/08. Additionally, females appear to travel further from the colony compared to males during both Incubation 2005/06 and Incubation 2007/08. Interestingly, during Incubation 2008/09 (Fig. 9) the distribution of tracked black petrels was further to the north than the previous two incubation phases (Figs. 3 & 4). The 50% density contour for male, female and all points in Incubation 2008/09 is not centred over the Hauraki Gulf as in previous incubation phases. Furthermore, the 95% contour for female points does not even include the Hauraki Gulf. Distribution during Incubation 2008/09 appears to stretch latitudinally across 30°S with 95% contours as far north as 11.6°S (Fig. 9). The 95%

contours during the incubation phases cover the largest areas, with the 95% and 50% contours from Incubation 2008/09 encompassing the largest areas of all breeding phases (Table 6).

Distribution patterns contract around the colony during Chick 2008 when birds are actively rearing chicks (Fig. 5). The 50% contour encompasses the Hauraki Gulf and stretches to the north for all density plots in Chick 2008. Apart from the Non-breeding phase, the area of the 95% contour is smallest during the Chick 2008 breeding phase (Table 6).

Kernel density contours of black petrel light-geolocator points during migrations east and west across the Pacific Ocean cover an area between 175°E to 95°W and 13°N to 50°S (Fig. 6). It appears that black petrels may migrate east in a more southerly route, and migrate back west toward New Zealand in a more northerly route.

Distribution during the non-breeding phase is concentrated off the coast of Ecuador (Fig. 7) with little variation by gender. Despite the large number of light-geolocator points used to generate the density contours during the Non-breeding 2008 phase (Table 4), the area covered by the 95% and 50% contours are the smallest of all breeding phases (Table 6). This indicates that black petrels concentrate their foraging effort during the non-breeding season in a relatively small area, even though the birds are not restricted by central place foraging as during breeding phases. The 50% contour for male, female and all points is centred over the Ecuadorian coast where oceanographic conditions, determined by the Equatorial Front and Humboldt Current, generate strong upwelling with subsequent increased primary production and secondary consumers such as forage fish for seabird predators (Cucalon 1989). The 95% contour includes the Galapagos Islands for all and female point contours (Fig. 7).

The Pre-egg 2008 breeding phase encompasses the shortest period of time (22 days, Table 4), during which time the black petrels used a diversity of areas (Fig. 8). The 95% contour stretches from 158°E to 146°W and 15°S to 40°S. The 50% contour of all points partially includes the Hauraki Gulf, yet the 50% contour for both males and females is to the north.

### 4.3.3 Habitat use patterns

Throughout all tests, no correlation between environmental variables was detected using Spearman's Rank correlation.

Habitat selection patterns during the incubation phases showed similarities and differences, which likely reflect changes in both habitat use and habitat availability (Tables 7-9, Figs. 10-21). During Incubation 2005/06 and Incubation 2007/08, light-geolocator points within the 50% contour were characterized by habitat with higher chlorophyll *a*, shallower depths, and less slope (Tables 7 & 9, Figs. 10 & 11). During Incubation 2005/06 birds also preferred habitat with cooler water temperatures and slightly lower SSH. Habitat used during Incubation 2005/06 was characterized by relatively very shallow depths (X=1118 m, SD=1290) and least slope (X=1.42 % rise, SD=0.36) compared to all other breeding phases (Figs. 20 & 21). However, during Incubation 2008/09 black petrels used habitat with the greatest slope (X=2.49 % rise, SD=0.95) and relatively deep water (X=3842 m, SD=1358). Additionally, Incubation 2008/09 was characterized by habitat use patterns in waters with the lowest chlorophyll *a* levels (X=0.074 mg $m^{-3}$, SD=0.048). Consistent habitat use differences by gender were also detected during both Incubation 2005/06 and Incubation 2007/08 with females strongly preferring habitats with greater depths than males (Table 8, Fig. 20). During Incubation 2007/08 males used habitats with higher chlorophyll *a* levels (Fig. 17) and less slope than females (Fig. 21). During Incubation 2008/09 habitat comparisons between the 50% and 95%

contours showed a preference for cooler waters and greater slope (Fig. 15). Females showed a strong preference for habitats with greater slope during Incubation 2008/09 (Fig. 21).

During Chick Rearing 2008 black petrels used habitat within the 50% density contour that had increased SSH, and was slightly deeper, warmer and with less slope (Tables 7 & 9, Fig. 12). No difference in chlorophyll *a* was detected. Differences in habitat use by gender indicated that females used habitat with greater slope than males (Tables 8 & 9, Fig. 21).

Strong habitat use patterns were detected during the non-breeding 2008 phase between the 50% and 95% density contours. Habitat within the 50% contour was characterized by shallower, more productive, and warmer water, with higher SSH and greater slope (Table 7 & 9, Fig. 13). Gender differences in habitat use during the non-breeding phase was only detected in depth and slope (Table 8), with males preferring shallower habitat (Fig. 20) and females occupying areas with slightly greater slope (Fig. 21). Unsurprisingly, overall habitat characteristics on the non-breeding grounds were different from habitat during the breeding phases within New Zealand. Habitat used off the coast of Ecuador featured much warmer water temperatures (Fig. 16), much higher chlorophyll *a* levels (Fig. 17), and a smaller range of depths (Fig. 20) and slope (Fig. 21).

Analysis of light-geolocator points during the Pre-egg 2008 breeding phase showed a significant preference for habitats with cooler temperatures, and for deeper areas with less slope (Tables 7 & 9, Fig. 14). Only a small gender difference in habitat use was detected; females showed a preference for habitat with higher SSH (Tables 8 & 9, Fig. 19). Interestingly, much deeper habitat was used during the Pre-egg 2008 phase (X=4702 m, SD=1286) compared to all other breeding phases (Fig. 20).

# 5 Discussion

The black petrel population on Great Barrier Island has been monitored since the 1995/96 breeding season (Bell & Sim 1998a, b, 2000a, b,c, 2002, 2003a, b, 2005; Bell et al 2007, 2009; Bell et al. 2011).

Little is known about the foraging range and at-sea distribution of the black petrel beyond anecdotal records from band recoveries, bird watching expeditions, fishermen, Ministry of Fisheries observers and other vessels (Bell et al 2011). Many records provide only general locations, and may be related to black petrels' habits of following boats to scavenge (rather than the routes they would follow in the absence of fishing boats).

A large scale of analysis (200 $km^2$ and 1 day) was undertaken in this study due to the spatial error associated with light-geolocator tracking technology. However, the large sample size of tracks and the long-term tracking record allowed good comparative results. Black petrels demonstrated large variability in habitat use patterns and foraging ranges. The integration of these results produces compelling findings on how these seabirds use foraging habitat relative to fisheries distribution (Bell et al, in prep).

Analysis of three years of tracking data while on breeding grounds in New Zealand indicates that black petrels shift habitat use patterns, a likely response to environmental variability. Such behavioural plasticity allows individuals to locate habitats with increased resource availability as environmental conditions change. This ability to exploit different areas is particularly evident when comparing habitat use patterns between the three incubation phases. Despite animals incurring the same demands of breeding and central place foraging, habitat use patterns between phases were variable between years, with Incubation 2008/09 being particularly distinct. Comparison of kernel density contours illustrates that during Incubation 2008/09 black petrels were distributed further northward than in the two other incubation phases. Unlike Incubation 2005/06 and Incubation 2007/08, the 50% contour does not include the Hauraki Gulf (Fig. 9), indicating that resource distribution was different in Incubation 2008/09, which caused birds to travel farther (Table 6) and use different areas. This distribution shift likely explains the change in habitat use characteristics: during Incubation 2008/09 black petrels used habitats with increased slope – a result not detected in previous incubation phases when other variables were significant (Table 9). This result reflects the fact that the 50% contour during Incubation 2008/09 overlaps the Kermadec, Colville, Three Kings and Norfolk ridges.

Oceanographic habitat exploited by black petrels in New Zealand is variable, giving black petrels a variety of habitats to potentially utilize. While on the breeding grounds in New Zealand, black petrels used habitat ranging from < 1000 m to > 5000 m deep (Fig. 19) and slope from 0.7 percent rise to > 4 percent rise (Fig. 21). Dynamic environmental variables SST, SSH and chlorophyll *a* within habitats used also varied between and within breeding phases in New Zealand (Figs. 16-19). The variety of environmental variables found to be significantly correlated with black petrel light-geolocator point distribution indicates that birds distribute themselves across available habitat based on resource distribution. Black petrels maintain flexible habitat use patterns when foraging to exploit habitats relative to the environmental variability.

No clear or consistent difference in habitat use between genders was detected. Males did use significantly shallower habitats in three breeding phases and female GLS points occurred in habitats with significantly higher slope during four breeding phases. It is difficult to determine based on these data whether these results are spurious or representative of real and consistent differences in habitat use by gender.

Interestingly, while on the non-breeding grounds off the coast of Ecuador the 50% and 95% contours of black petrel distribution covered the smallest area compared to other breeding seasons (Table 6). This result is despite a lack of distribution limitations on the birds due to central place foraging, and the non-breeding phase spanning seven months and including over 1000 GLS points. All habitat characteristics analyzed were significantly different between the 50% and 95% contours during the non-breeding phase (Table 9). Black petrels used habitats with warmer water and higher chlorophyll *a* levels than during any other breeding phase.

It is important to continue to monitor the Great Barrier Island black petrel population. Long-term population data combined with improved technology and further use of data-loggers can be used to develop an accurate population model to determine adult survivorship, recruitment, mortality and productivity as well as assess factors affecting the black petrel population on land and at-sea, particularly changes in habitat, foraging zones and prey species and identifying risks (such as fisheries interaction, predators and climate change).

## 6 Recommendations

The authors recommend that:

- Monitoring of the black petrel population (using the study burrows) is continued at Great Barrier Island up to and including the 2024/25 breeding season. This will ensure that 25 years of comparative data are collected to determine the population dynamics of black petrels, allowing us to develop a multi-generational population model to determine survivorship, mortality and the effects of predation, fishing interaction and other environmental factors.
- The colony continues to be visited three times per season; November/December (allowing a large number of birds to be banded or recaptured easily, as the birds are often outside the burrows during this period), January/February and April/May (allowing time for chicks to be banded before they fledge). A high rate of banding and recapture will enable the continuation of the mark-recapture programme.
- The study burrows should be checked for breeding status during every visit to the study area, to give a more accurate estimate of breeding success and determine sex of adults. This would also provide an opportunity to recapture returning birds banded as chicks.
- A sample of 50 black petrels should carry GPS and light-geolocator data-loggers over two or three breeding seasons to accurately investigate foraging distances and

locations, water temperature and flight patterns throughout the breeding and non-breeding seasons.

- Random transect surveys throughout the 35-ha study area around Mount Hobson are undertaken every five years to increase the likelihood of adult and juvenile recaptures (improving the accuracy of survival and immigration estimates) and to be used to estimate population trends.
- Cat trapping should be implemented before and during the black petrel breeding season, November to June, especially during pre-laying (October/November) and the fledging period (May to June).

## 7 Acknowledgements

This project was funded by the Department of Conservation (Science Investigation No. POP2009/01). Halema Jamieson and Joanna Sim (DOC, Great Barrier Island) assisted with transport around Great Barrier Island, logistical support and in the field. Conori Bell, Heather Smithers, Paul Garner-Richards and Mark Fraser assisted in the field. Kelvin Floyd developed and designed Figure 1 and also assisted in the field. David Thompson (NIWA) provided LOTEK™ light geolocators for the 2005/06 season. Mike Imber and the DOC Banding Office provided details on the black petrel banding records.

## 8 References

Bell, E.A.; Sim, J.L. 1998a. *Survey and monitoring of black petrels on Great Barrier Island 1996. Science for Conservation:77*. Department of Conservation, Wellington.

Bell, E.A.; Sim, J.L. 1998b. *Survey and monitoring of black petrels on Great Barrier Island 1997. Science for Conservation:78*. Department of Conservation, Wellington.

Bell, E.A.; Sim, J.L. 2000a. *Survey and monitoring of black petrels on Great Barrier Island 1997/98.* Published client report on contract 3085, funded by Conservation Services Levy. Department of Conservation, Wellington. 24 p.

Bell, E.A.; Sim, J.L. 2000c. *Survey and monitoring of black petrels on Great Barrier Island 1999/2000.* Published client report on contract 3018, funded by Conservation Services Levy. Department of Conservation, Wellington. 30 p.

Bell, E.A.; Sim, J.L. 2000b. *Survey and monitoring of black petrels on Great Barrier Island 1998/99.* Published client report on contract 3089, funded by Conservation Services Levy. Department of Conservation, Wellington. 23 p.

Bell, E.A.; Sim, J.L. 2002. Survey and monitoring of black petrels on Great Barrier Island 2000/01. *DOC Science Internal Series 48.* Department of Conservation, Wellington. 24 p.

Bell, E.A.; Sim, J.L. 2003a. Survey and monitoring of black petrels on Great Barrier Island 2001/02. *DOC Science Internal Series 134.* Department of Conservation, Wellington. 24p.

Bell, E.A.; Sim, J.L. 2003b. Survey and monitoring of black petrels on Great Barrier Island 2002/03. *DOC Science Internal Series 135.* Department of Conservation, Wellington. 28p.

Bell, E.A.; Sim, J.L. 2005. Survey and monitoring of black petrels on Great Barrier Island 2003/04. *DOC Research and Development Series 213.* Department of Conservation, Wellington. 27p.

Bell, E.A.; Sim, J.L.; Scofield, P. 2007. Demographic parameters of the black petrel (*Procellaria parkinsoni*). *DOC Research and Development Series 273.* Department of Conservation, Wellington. 32p.

Bell, E.A.; Sim, J.L.; Scofield, P. 2009. Population parameters and distribution of the black petrel (*Procellaria parkinsoni*), 2005/06. *DOC Research and Development Series 307.* Department of Conservation, Wellington. 47p.

Bell, E.A.; Sim, J.L.; Scofield, P. 2011. At-sea distribution and population dynamics of the black petrel (*Procellaria parkinsoni*), 2007/08. *DOC Marine Conservation Services Series 8.* Department of Conservation, Wellington. 37p.

Cucalon, E. 1989. Oceanographic characteristics off the coast of Ecuador. In: Olsen, S.; Arriaga, L. (eds). A sustainable shrimp mariculture industry for Ecuador, pp. University of Rhode Island, Narragansett, RI: Coastal Resources Center.

Freeman, R.; Dennis,T.; Landers, T.l.; Thompson, D.R.; Bell, E.; Walker, M.; Guildford, T.C. 2010. Black petrel (*Procellaria parkinsoni*) patrol the ocean shelf-break: GPS tracking of a vulnerable procellariform seabird. *PLoS One* 5(2): e9236.

Heather, B. and Robertson, H. 1996. Field guide to the birds of New Zealand. Penguin Book (NZ) Ltd, Auckland, New Zealand. 432p.

Imber, M.J. 1987. Breeding ecology and conservation of the black petrel (*Procellaria parkinsoni*). *Notornis* 34: 19-39.

Phillips, R.A.; Silk, J.R.D.; Croxall, J.P.; Afanasyev, V. 2006. Year-round distribution of white-chinned petrels from South Georgia: Relationships with oceanography and fisheries. *Biological Conservation* 129: 336-347.

Phillips, R.A.; Silk, J.R.D.; Croxall, J.P.; Afanasyev, V.; Briggs, D.R. 2004. Accuracy of geolocation estimates for flying seabirds. *Marine Ecology Progress Series* 266: 265-272.

Shaffer, S.A.; Tremblay, Y.; Awkerman, J.A.; Henry, R.W.; Teo, S.L.H.; Anderson, D.J.; Croll, D.A.; Block, B.B.; Costa, D.P. 2005. Comparison of light- and SST-based geolocation with satellite telemetry in free-ranging albatrosses. *Marine Biology* 147: 833-843.

Shaffer, S.A.; Tremblay, Y.; Weimerskirch, H.; Scott, D.; Thompson, D.R.; Sagar, P.M.; Moller, H.; Taylor, G.A.; Foley, D.G.; Block, B.B.; Costa, D.P. 2006. Migratory shearwaters integrate oceanic resources across the Pacific Ocean in an endless summer. *Proceedings of the National Academy of Science* 103(34): 12799-12802.

Figures

Figure 1 Location of the black petrel (*Procellaria parkinsoni*) study burrows and census grids within the study area on Great Barrier Island (Aotea Island). Altitude (621 m a.s.l.) is shown. Approximate North is shown (N). KDG = Kauri Dam Grid; SFG = South Forks Grid; PTG = Palmers Track Grid.

Figure 2 Four examples of light-geolocator tracks of black petrels (*Procellaria parkinsoni*) demonstrating the original error in tracks using only SST-based latitudes (pre-filtered) and improved spatial location of tracks derived through speed filter using both SST-based and light-based latitudes (post-filtered).
Please ignore black horizontal lines in maps as these are artefacts of plotting in Matlab.

Figure 3 Kernel density plots of black petrel (*Procellaria parkinsoni*) light-geolocator points during Incubation 2005/06 by female (red), male (blue) and all (green) light-geolocator points. Darkest shade of colour represents the 50% contour, middle shade is the 75% contour, and the lightest shade is the 95% contour. Yellow star indicates location of breeding colonies in Hauraki Gulf.

Figure 4 Kernel density plots of black petrel (*Procellaria parkinsoni*) light-geolocator points during Incubation 2007/08 by female (red), male (blue), and all (green) light-geolocator points. Darkest shade of colour represents the 50% contour, middle shade is the 75% contour, and the lightest shade is the 95% contour. Yellow star indicates location of breeding colonies in Hauraki Gulf.

Figure 5 Kernel density plots of black petrel (*Procellaria parkinsoni*) light-geolocator points during Chick Rearing 2008 by female (red), male (blue), and all (green) light-geolocator points. Darkest shade of colour represents the 50% contour, middle shade is the 75% contour, and the lightest shade is the 95% contour. Yellow star indicates location of breeding colonies in Hauraki Gulf.

Figure 6 Kernel density plots of black petrel (*Procellaria parkinsoni*) light-geolocator points during (a) the Migration east 2008, and (b) the Migration west 2008. Darkest shade of green represents the 50% contour, middle shade is the 75% contour, and the lightest shade is the 95% contour. Yellow star indicates location of breeding colonies in Hauraki Gulf.

Figure 7 Kernel density plots of black petrel (*Procellaria parkinsoni*) light-geolocator points during the Non-breeding phase 2008 by female (red), male (blue), and all (green) light-geolocator points. Darkest shade of colour represents the 50% contour, middle shade is the 75% contour, and the lightest shade is the 95% contour.

Figure 8 Kernel density plots of black petrel (*Procellaria parkinsoni*) light-geolocator points during Pre-egg 2008 by female (red), male (blue), and all (green) light-geolocator points. Darkest shade of colour represents the 50% contour, middle shade is the 75% contour, and the lightest shade is the 95% contour. Yellow star indicates location of breeding colonies in Hauraki Gulf.

Figure 18 Lower range of box plots comparing chlorophyll *a* (mg $m^{-3}$) at black petrel (*Procellaria parkinsoni*) light-geolocator points within the 50% density contour, within and between breeding phases. Red boxes represent all light-geolocator points. Green boxes represent male light-geolocator points. Blue boxes represent female light-geolocator points. Box plots depict the interquartile range (IQR). Medians represented by red lines. Each red cross is an outlier and is > 1.5 * IQR.

Figure 19 Box plots comparison of SSH (cm) at black petrel (*Procellaria parkinsoni*) light-geolocator points within the 50% density contour, within and between breeding phases. Red boxes represent all light-geolocator points. Green boxes represent male light-geolocator points. Blue boxes represent female light-geolocator points. Box plots depict the interquartile range (IQR). Medians represented by red lines. Each red cross is an outlier and is > 1.5 * IQR.

Figure 20 Box plots comparison of depth (m) at black petrel (*Procellaria parkinsoni*) light-geolocator points within the 50% density contour, within and between breeding phases. Red boxes represent all light-geolocator points. Green boxes represent male light-geolocator points. Blue boxes represent female light-geolocator points. Box plots depict the interquartile range (IQR). Medians represented by red lines. Each red cross is an outlier and is > 1.5 * IQR.

Figure 21 Box plots comparison of slope (percent rise) at black petrel (*Procellaria parkinsoni*) light-geolocator points within the 50% density contour, within and between breeding phases. Red boxes represent all light-geolocator points. Green boxes represent male light-geolocator points. Blue boxes represent female light-geolocator points. Box plots depict the interquartile range (IQR). Medians represented by red lines. Each red cross is an outlier and is > 1.5 * IQR.

Tables

Figure 1

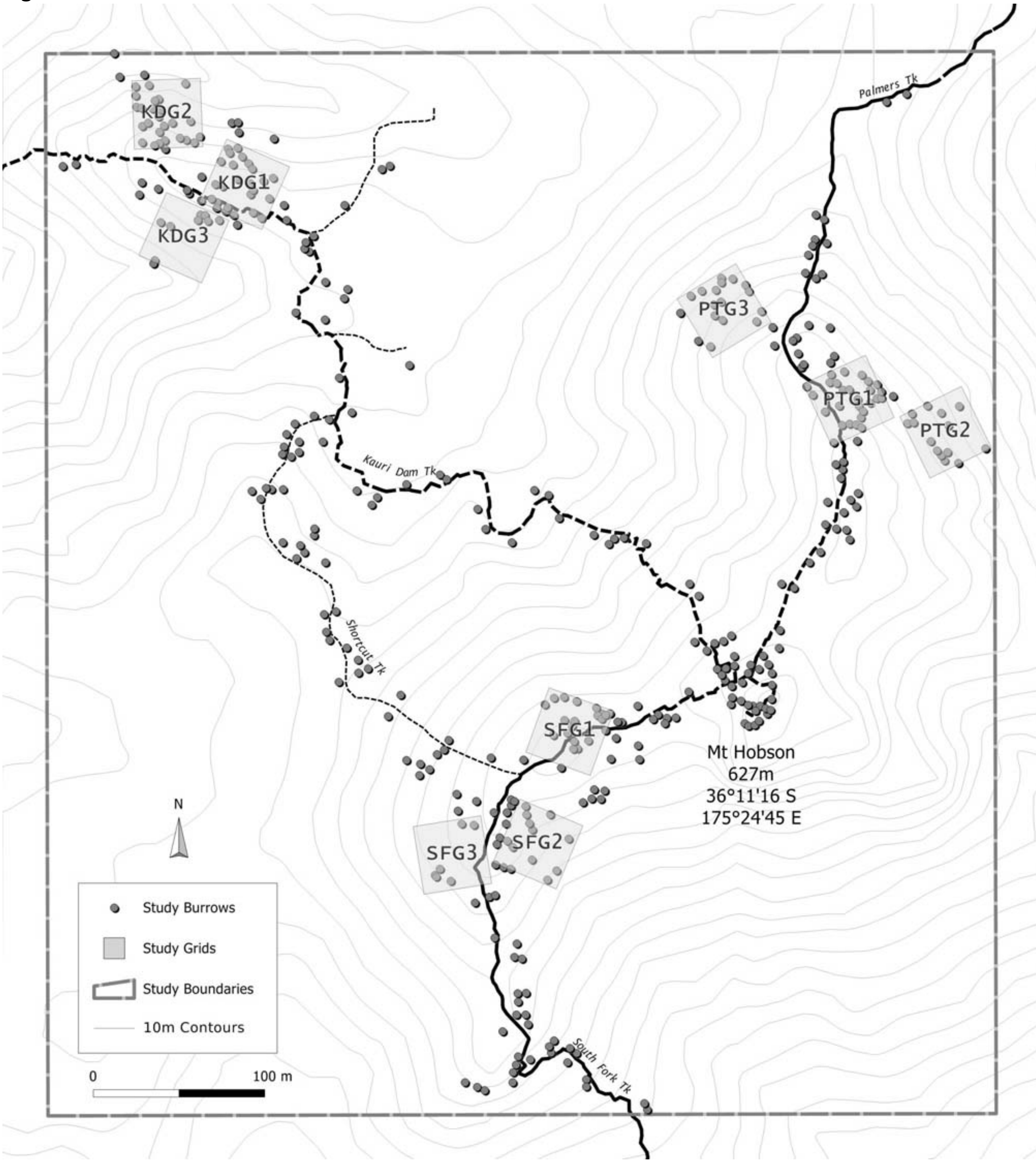
KDG2
KDG1
KDG3
PTG3
PTG1
PTG2
SFG1
SFG2
SFG3
Palmers Tk
Kauri Dam Tk
Shortcut Tk
South Fork Tk
Mt Hobson
627m
36°11'16 S
175°24'45 E
N
Study Burrows
Study Grids
Study Boundaries
10m Contours
0
100 m

Figure 2

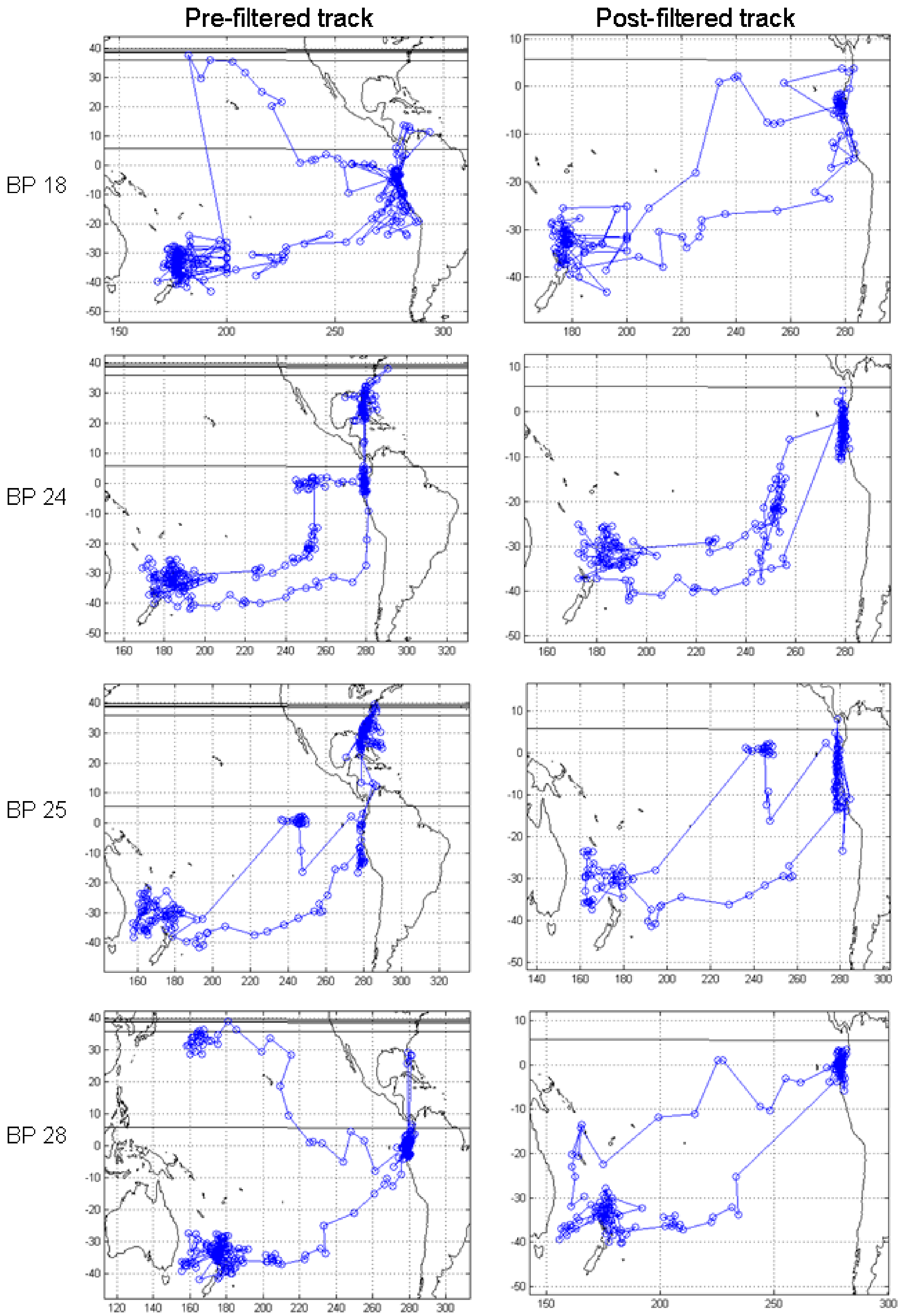

Figure 3

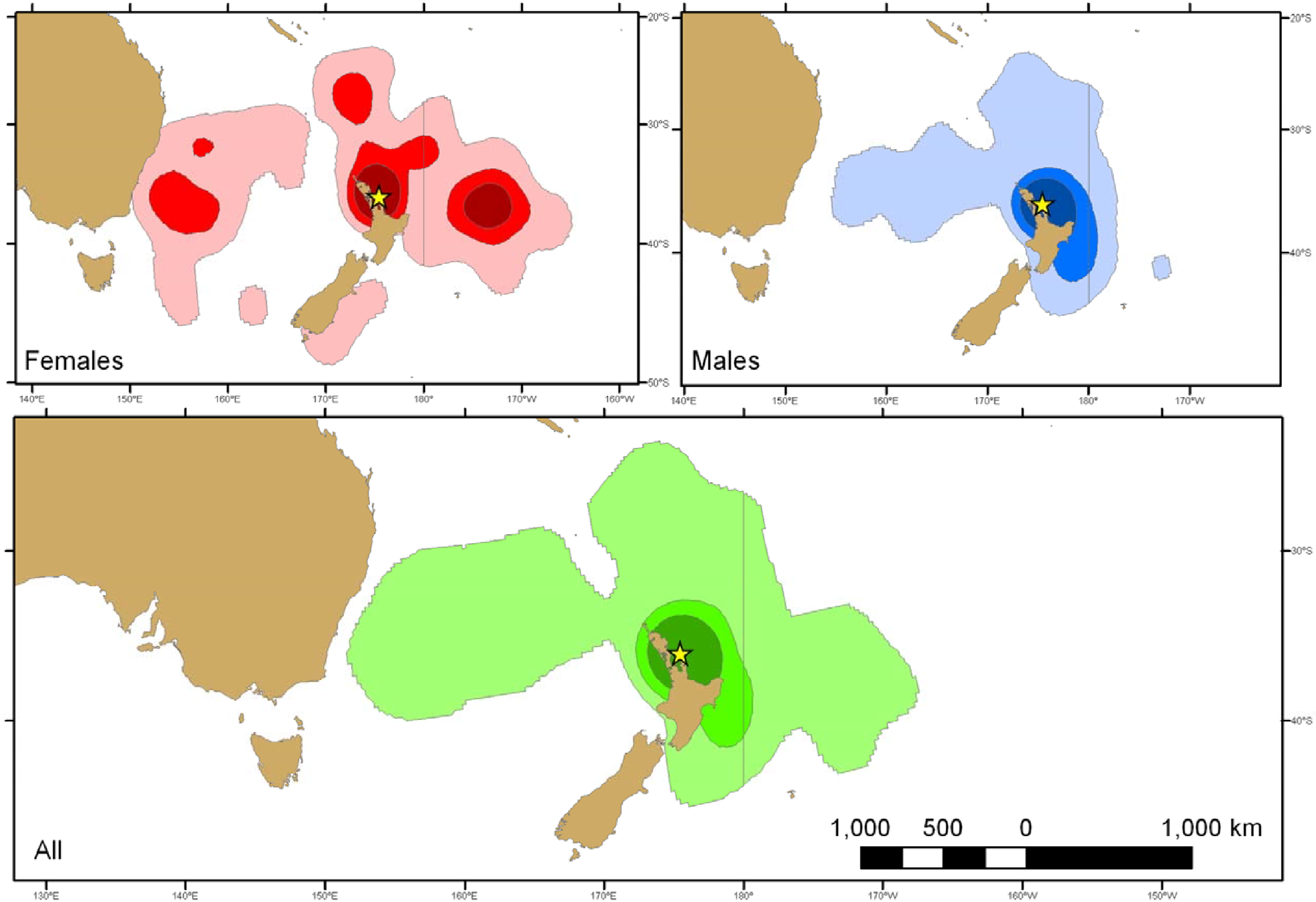

Figure 4

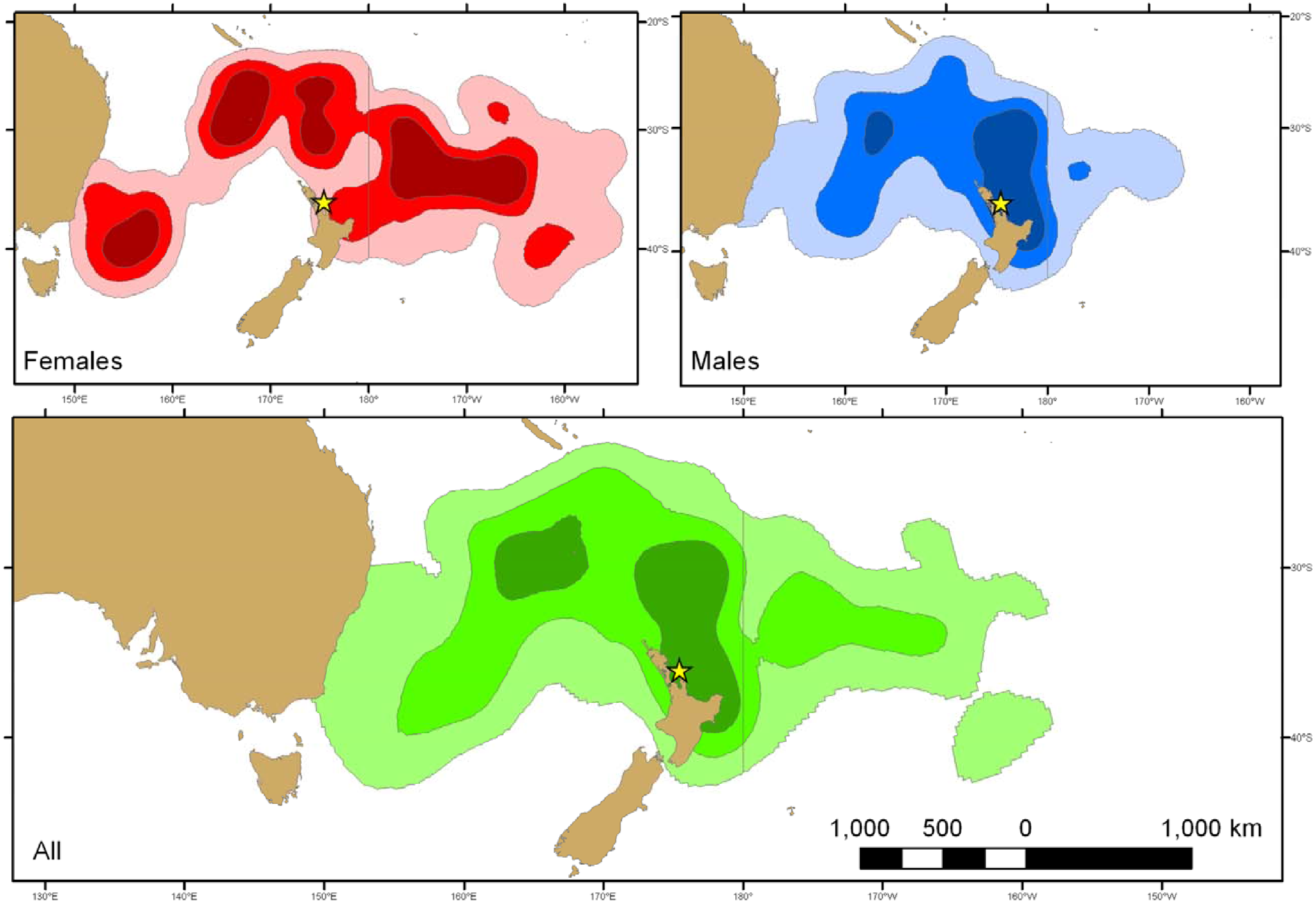
Females
Males
All
1,000 500 0 1,000 km
150°E
160°E
170°E
180°
170°W
160°W
20°S
30°S
40°S
130°E
140°E
150°W

Figure 5

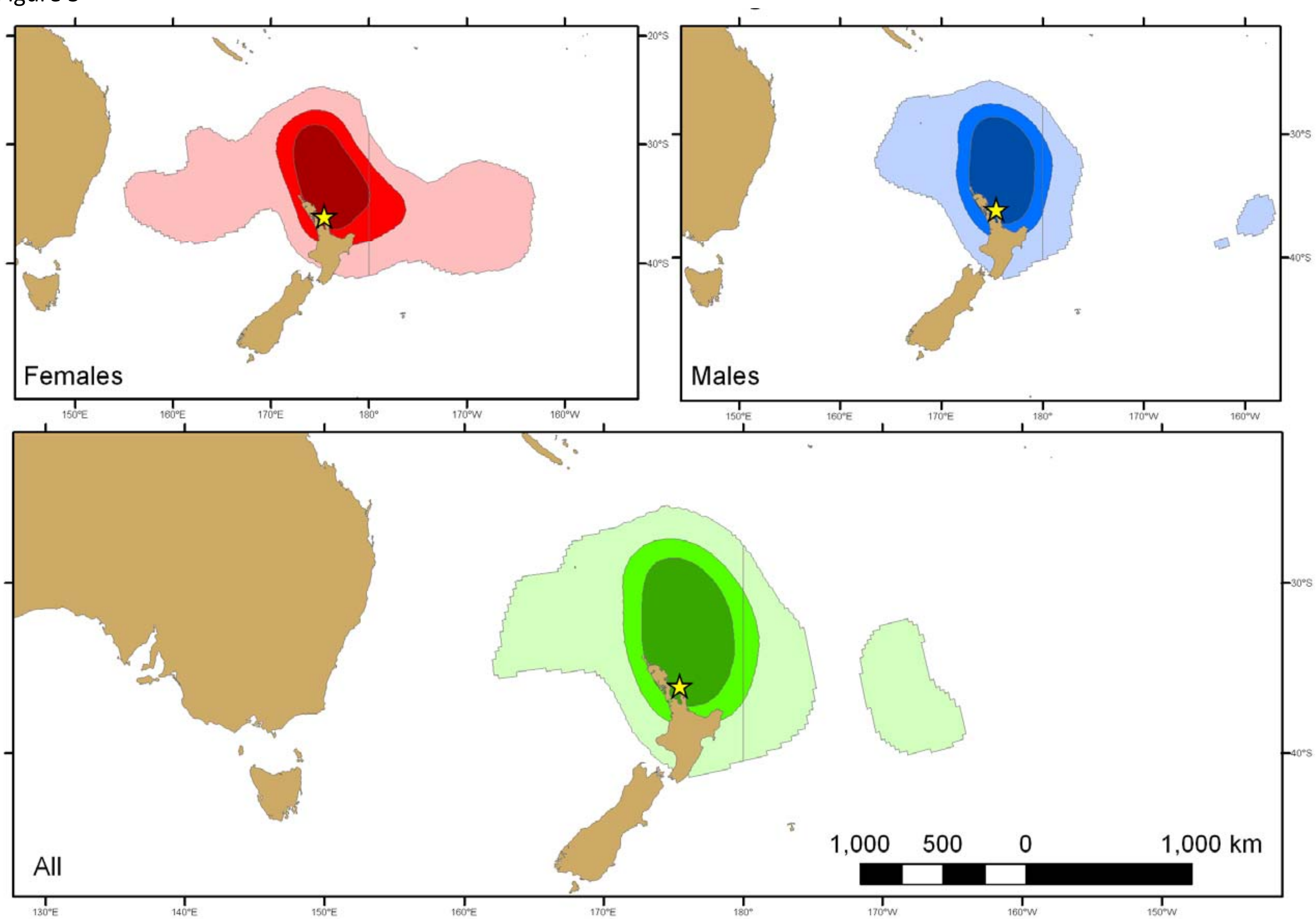
Females
Males
All
1,000 500 0 1,000 km
20°S
30°S
40°S
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W

Figure 6

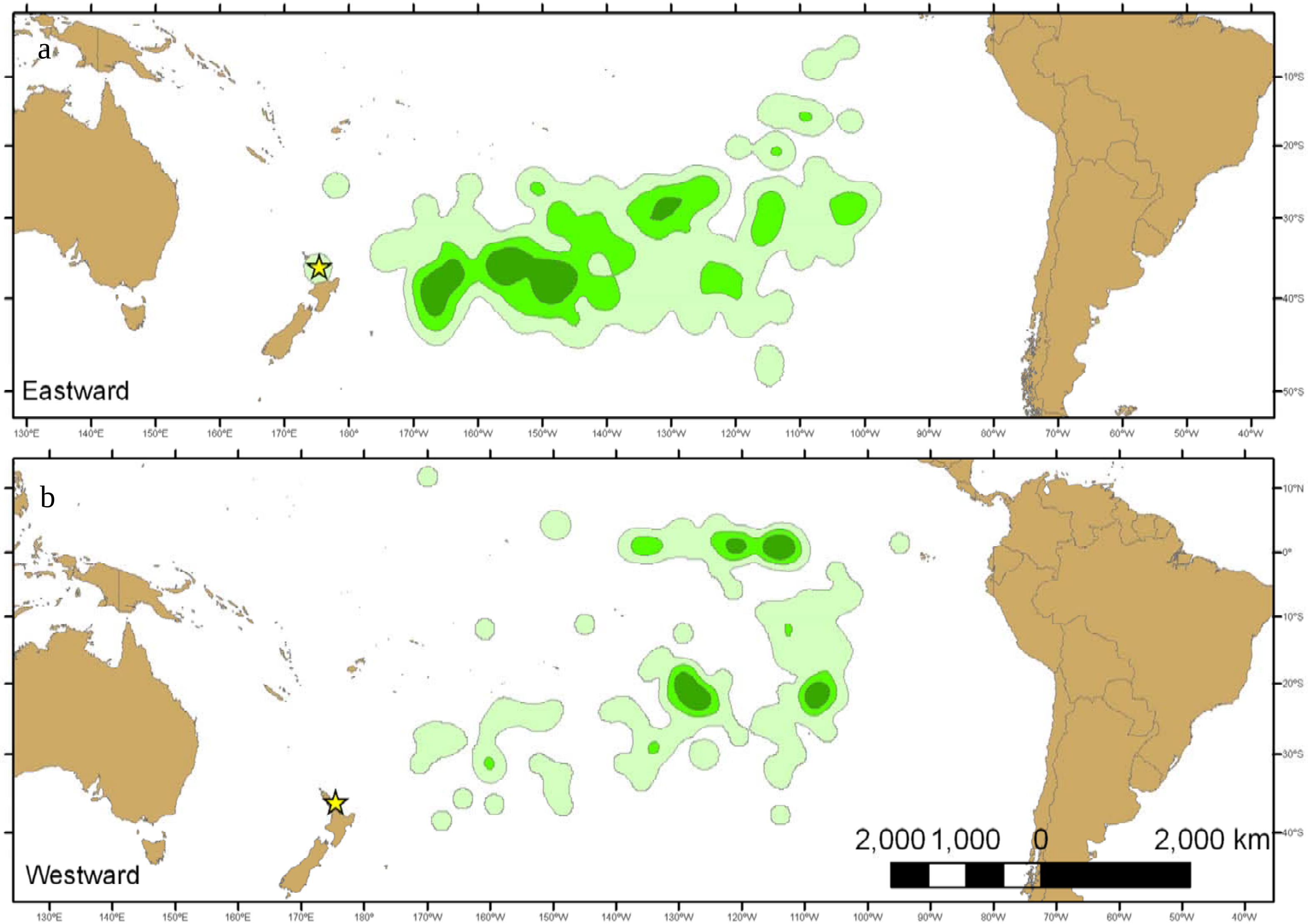

Figure 7

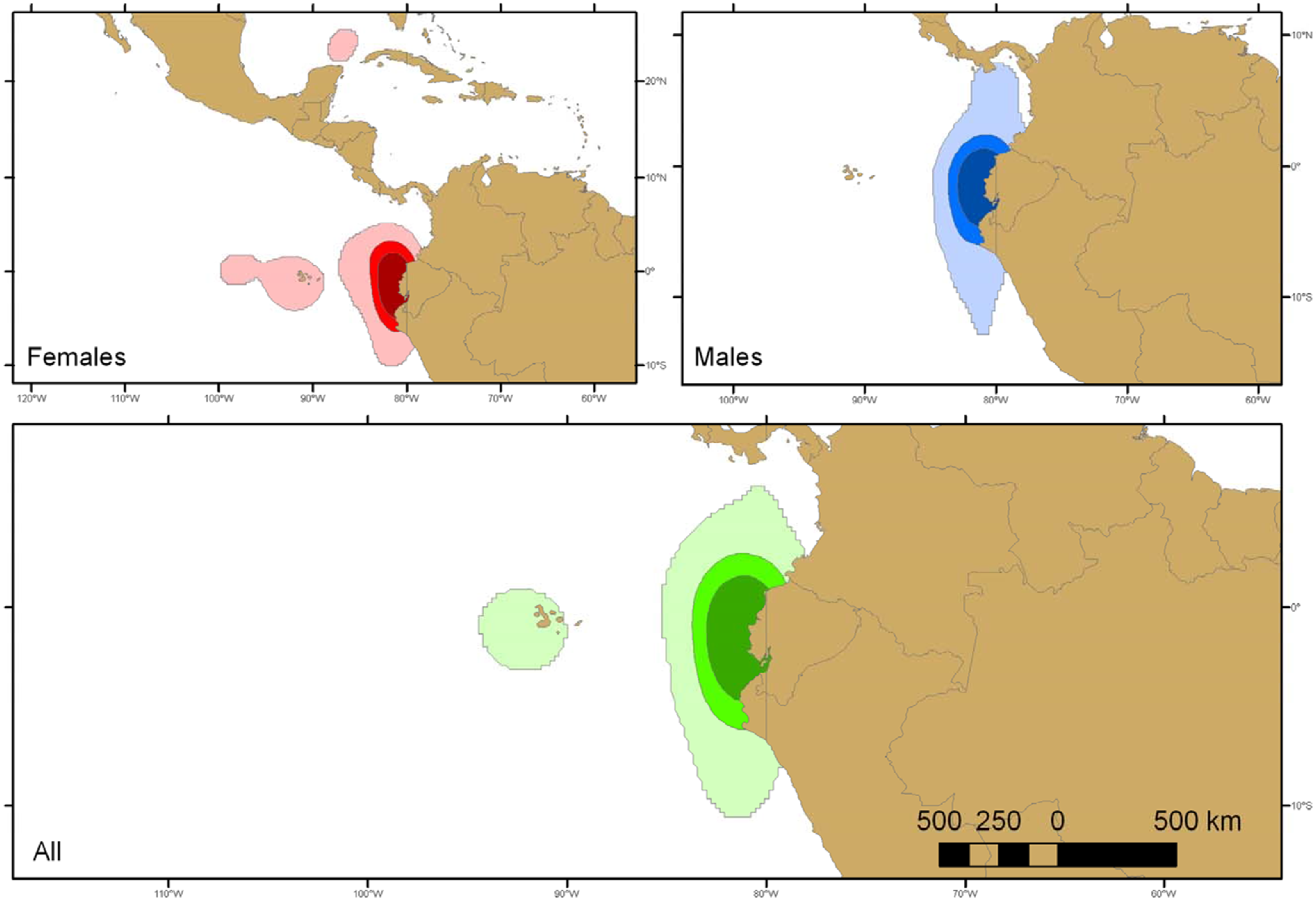
Females
Males
All
500 250 0 500 km
120°W
110°W
100°W
90°W
80°W
70°W
60°W
20°N
10°N
0°
10°S

Figure 8

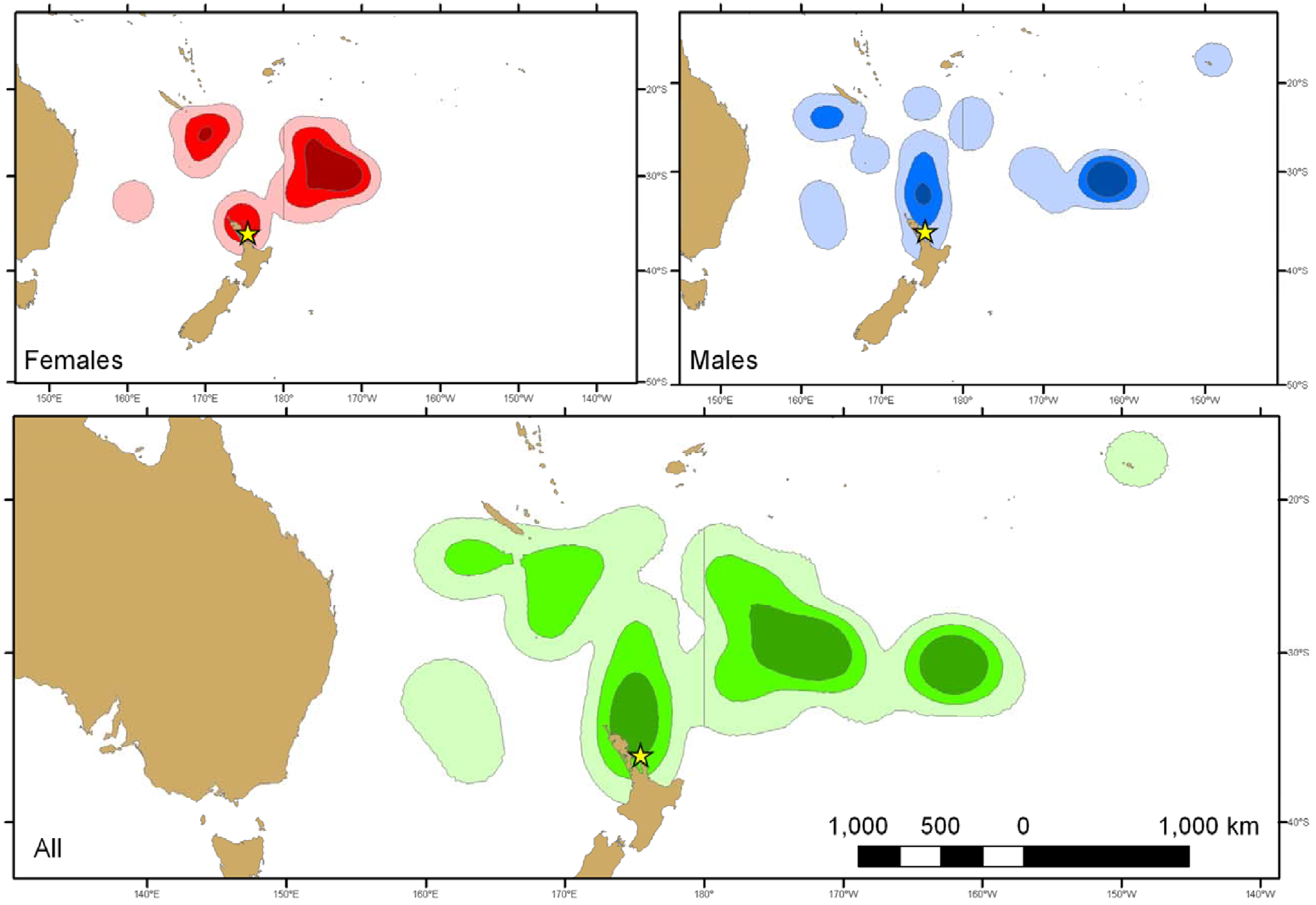
Females
Males
All
1,000 500 0 1,000 km
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
140°E
20°S
30°S
40°S
50°S

Figure 9

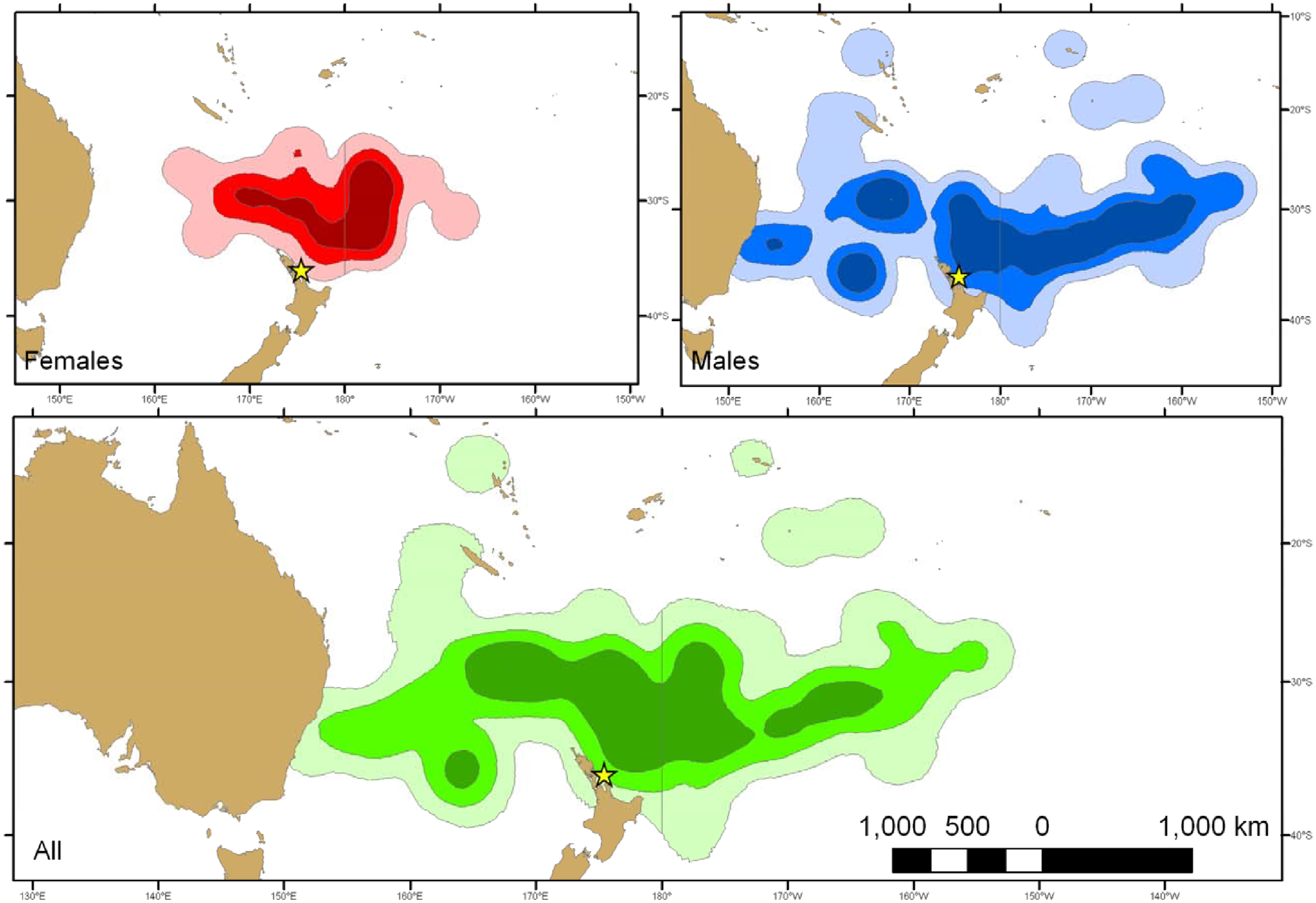
Females
Males
All
1,000 500 0 1,000 km
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°E
140°E
10°S
20°S
30°S
40°S

Figure 10

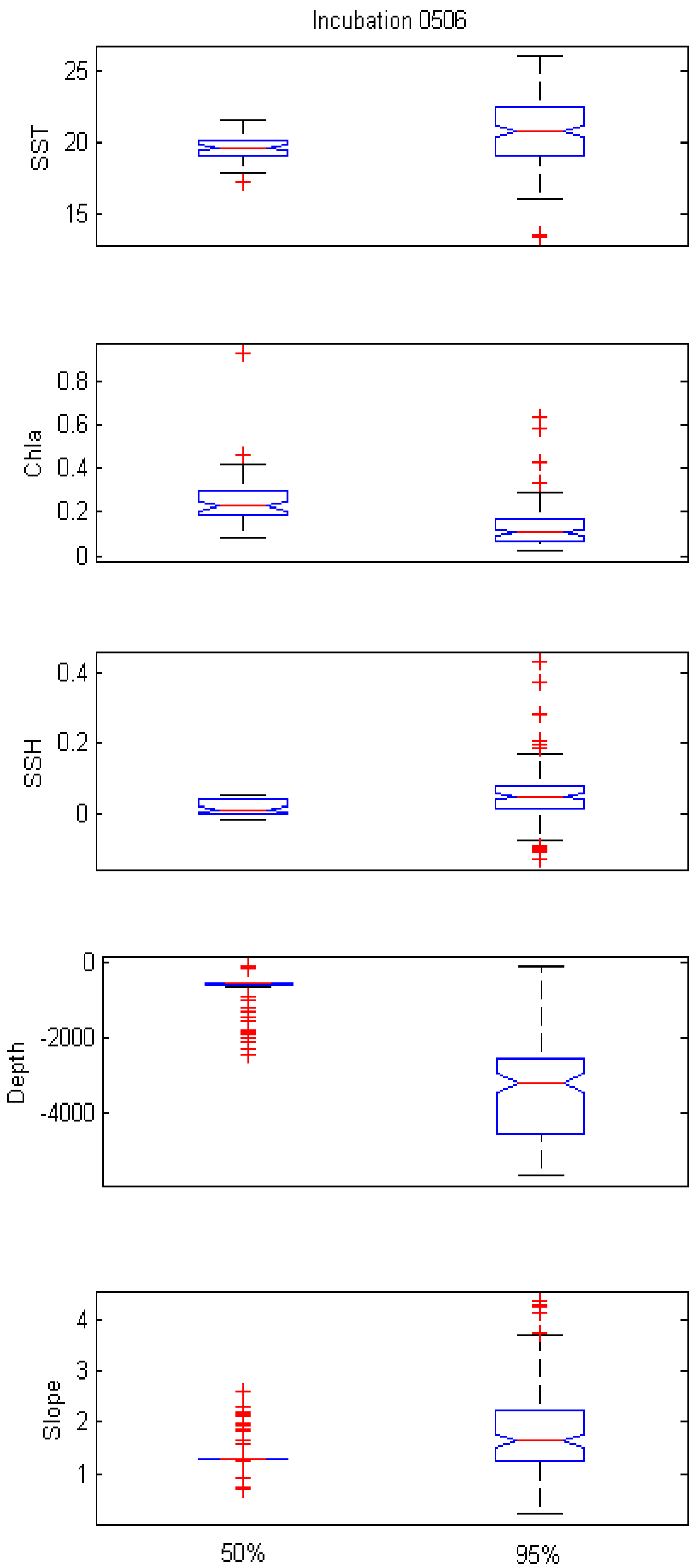
Incubation 0506
SST
25
20
15
Chla
0.8
0.6
0.4
0.2
0
SSH
0.4
0.2
0
Depth
0
-2000
-4000
Slope
4
3
2
1
50%
95%

Figure 11

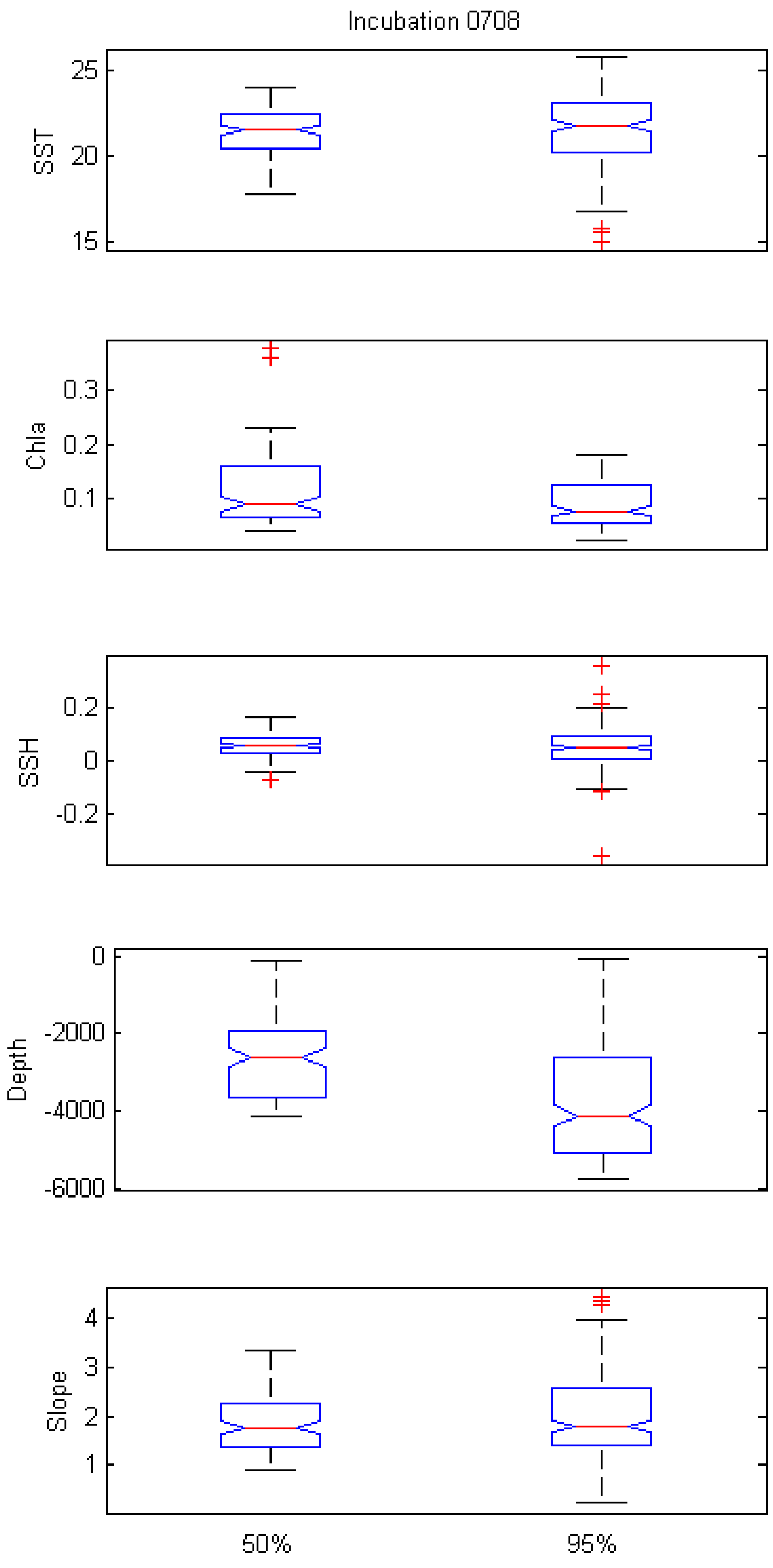
Incubation 0708
SST
25
20
15
Chla
0.3
0.2
0.1
SSH
0.2
0
-0.2
Depth
0
-2000
-4000
-6000
Slope
4
3
2
1
50%
95%

Figure 12

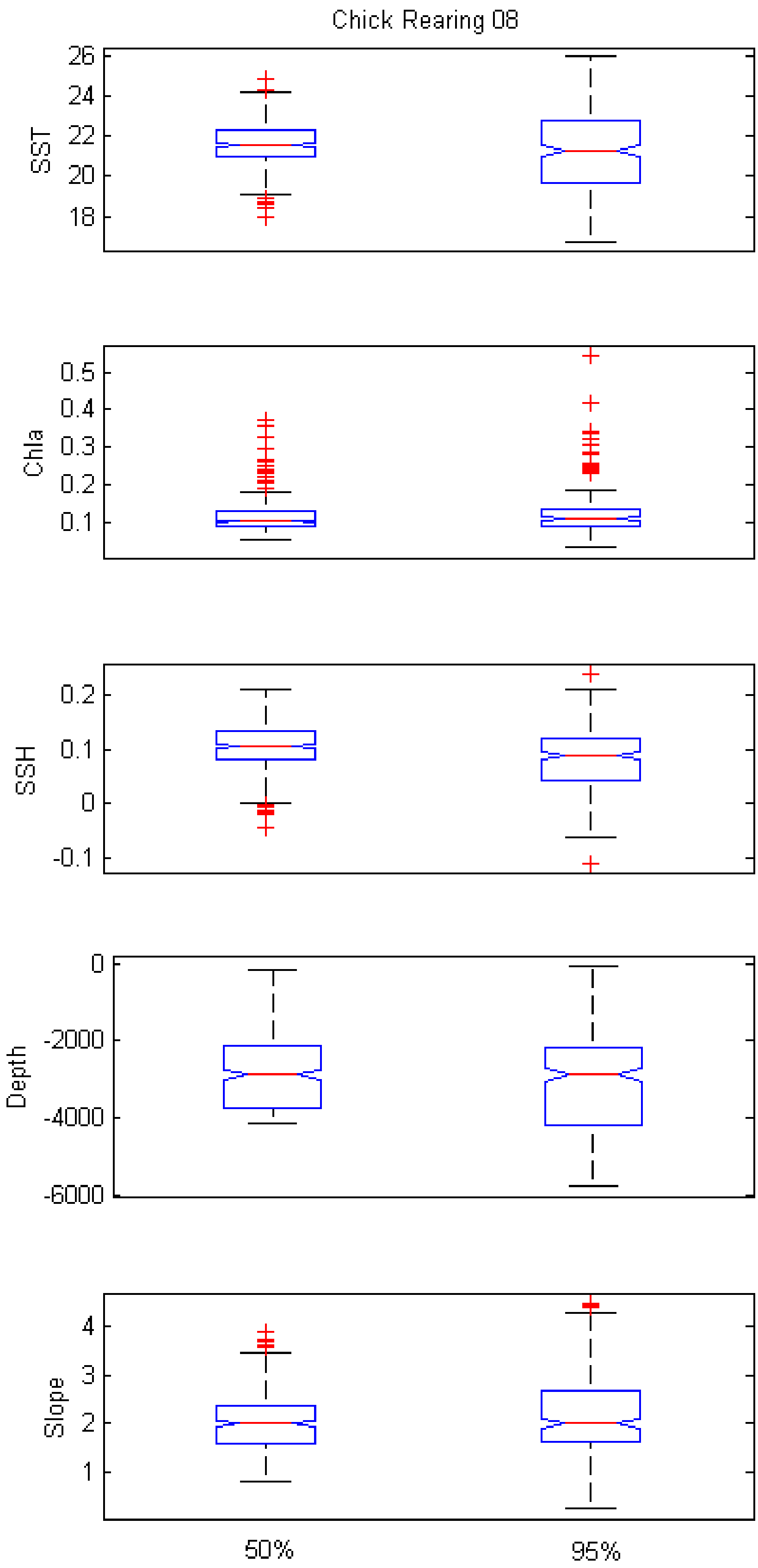
Chick Rearing 08
SST
26
24
22
20
18
Chla
0.5
0.4
0.3
0.2
0.1
SSH
0.2
0.1
0
-0.1
Depth
0
-2000
-4000
-6000
Slope
4
3
2
1
50%
95%

Figure 13

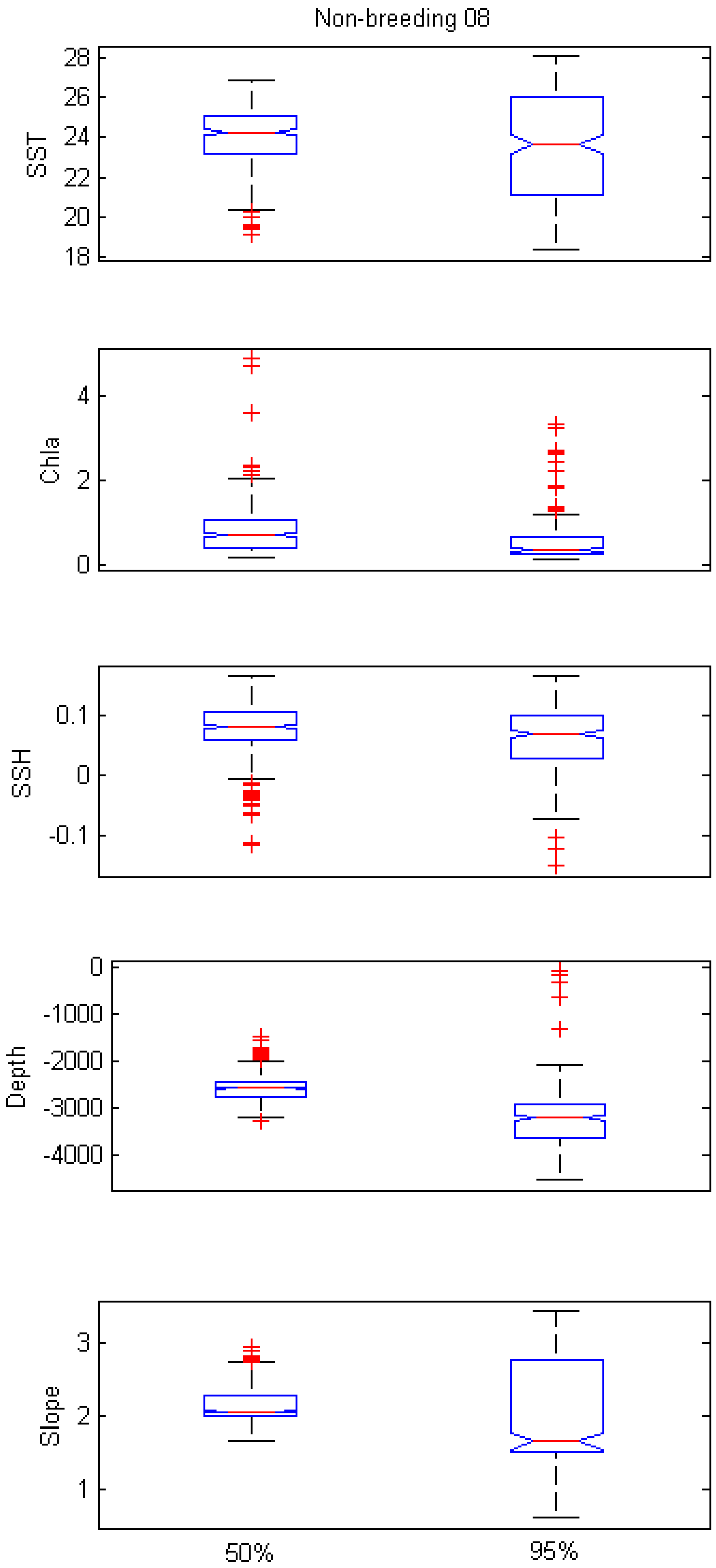
Non-breeding 08
SST
28
26
24
22
20
18
Chla
4
2
0
SSH
0.1
0
-0.1
Depth
0
-1000
-2000
-3000
-4000
Slope
3
2
1
50%
95%

Figure 14

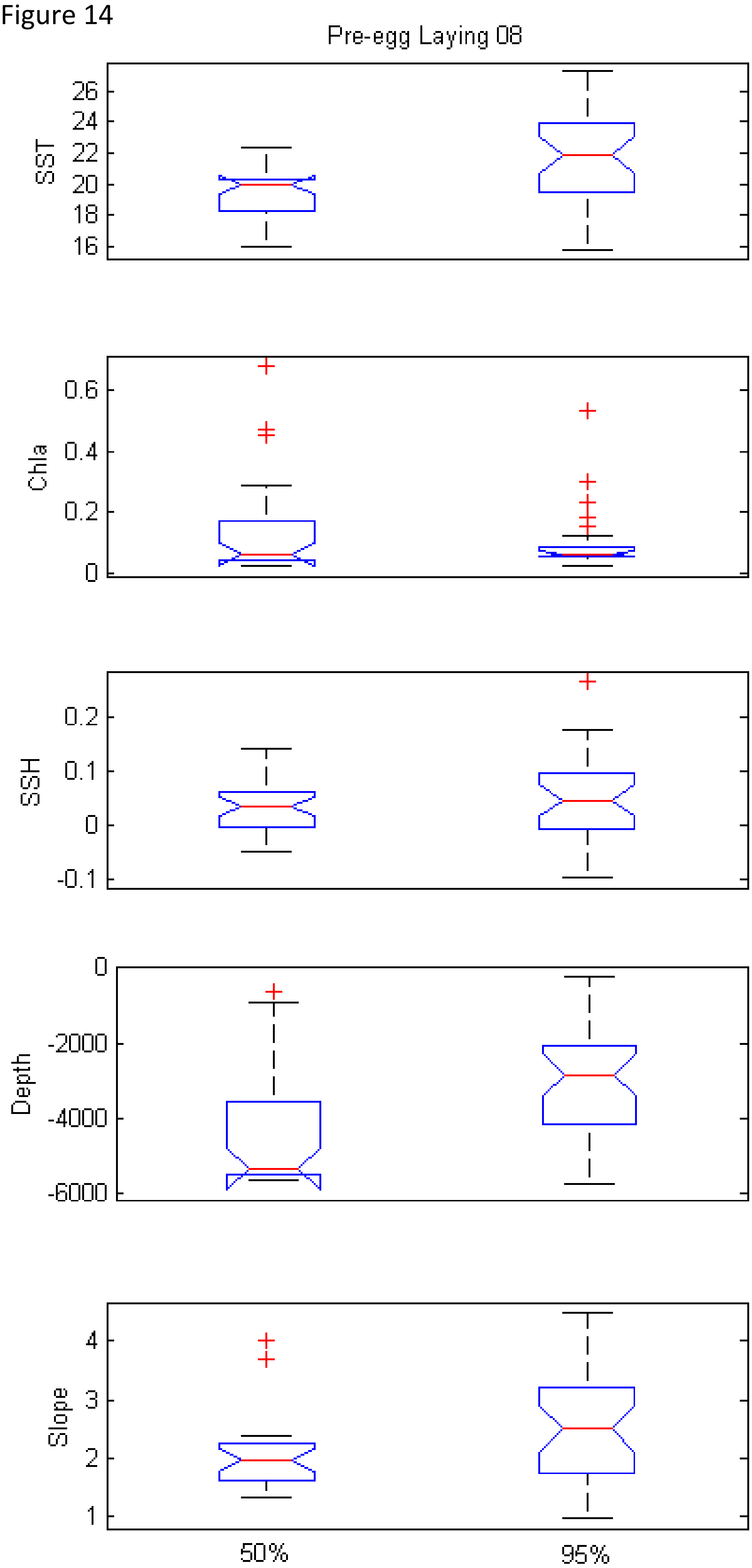
Pre-egg Laying 08
SST
26
24
22
20
18
16
Chla
0.6
0.4
0.2
0
SSH
0.2
0.1
0
-0.1
Depth
0
-2000
-4000
-6000
Slope
4
3
2
1
50%
95%

Figure 15

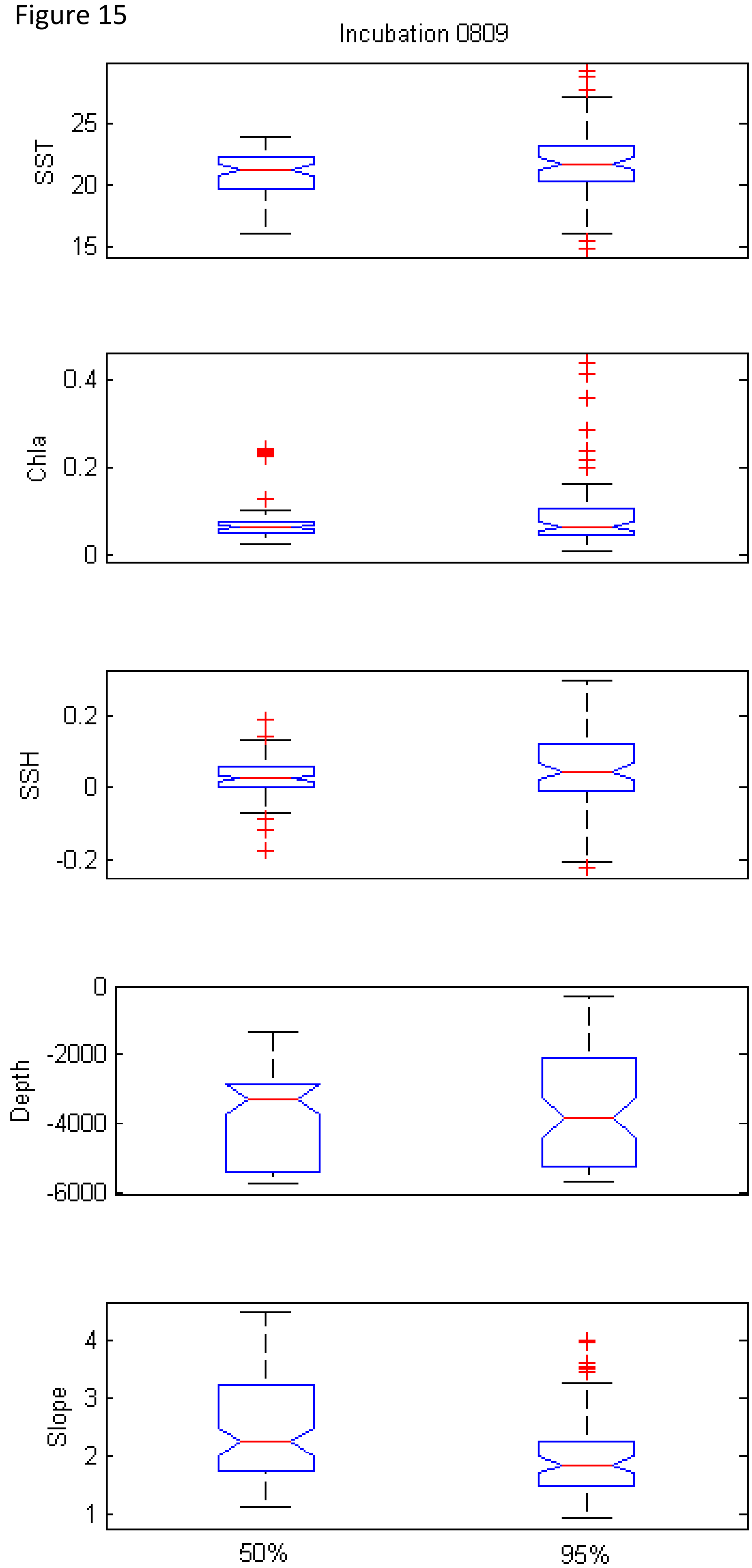
Incubation 0809
SST
25
20
15
Chla
0.4
0.2
0
SSH
0.2
0
-0.2
Depth
0
-2000
-4000
-6000
Slope
4
3
2
1
50%
95%

Figure 16

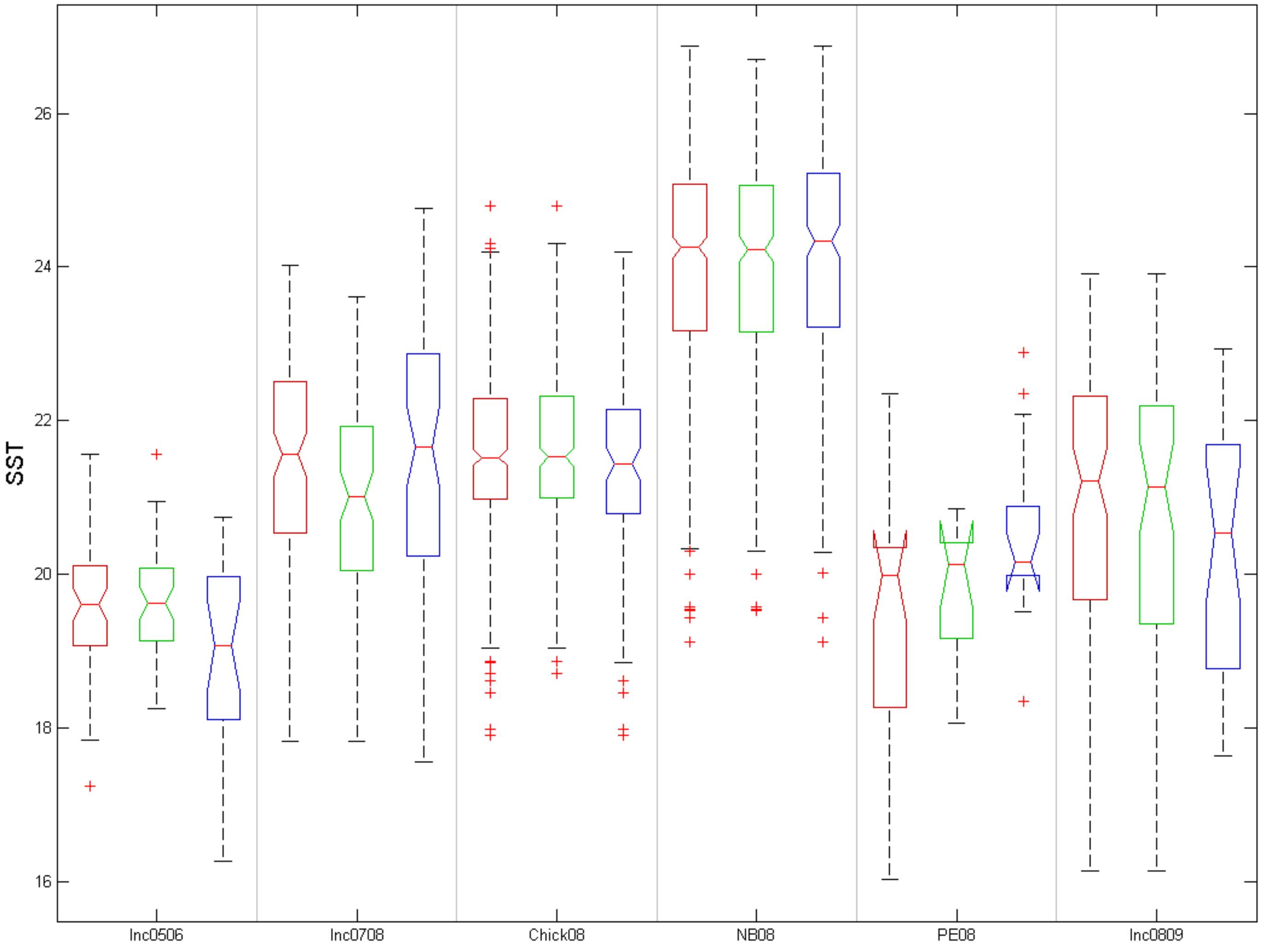
SST
26
24
22
20
18
16
Inc0506
Inc0708
Chick08
NB08
PE08
Inc0809

Figure 17

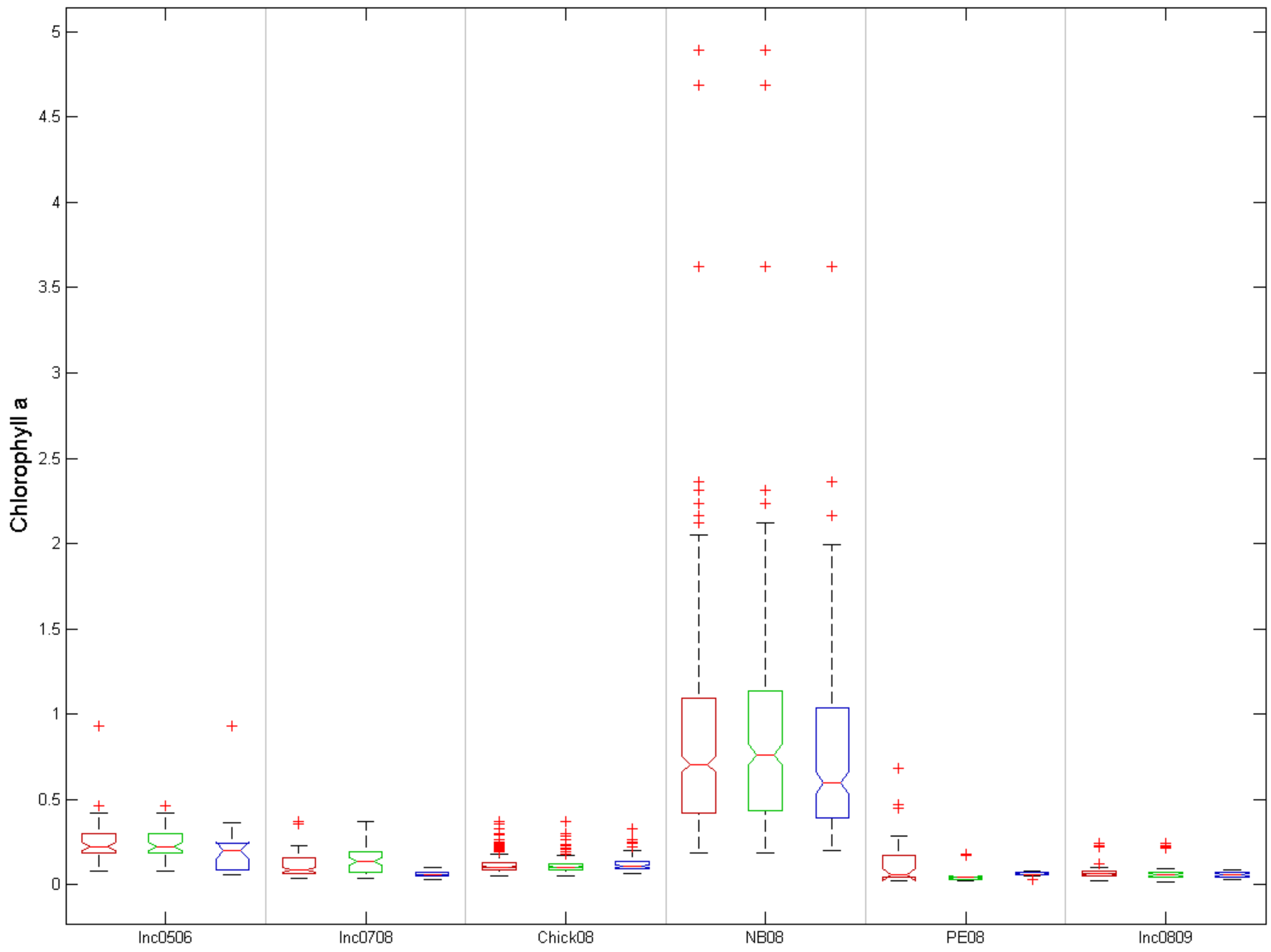
Chlorophyll a
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Inc0506
Inc0708
Chick08
NB08
PE08
Inc0809

Figure 18

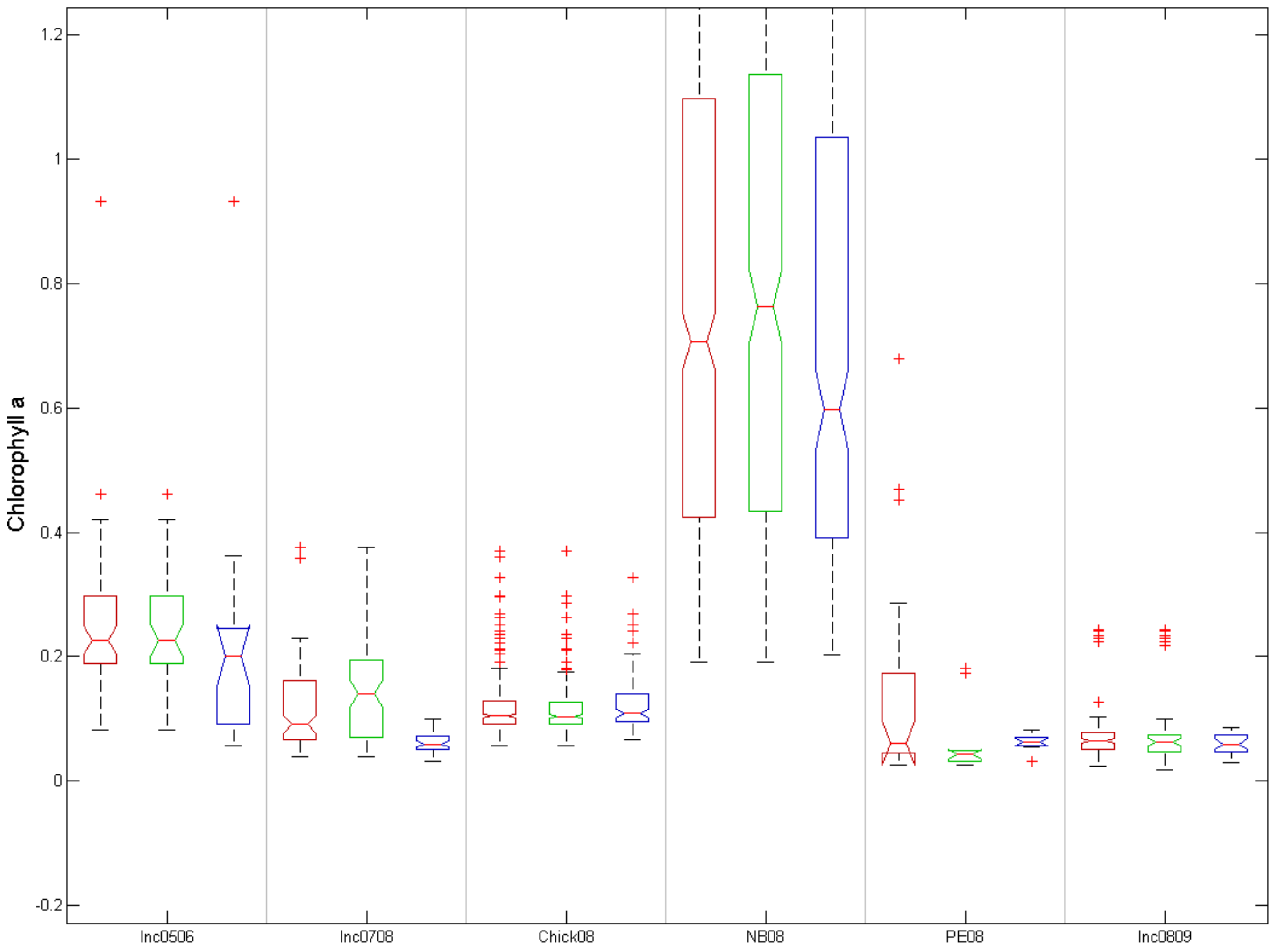
Chlorophyll a
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Inc0506
Inc0708
Chick08
NB08
PE08
Inc0809

Figure 19

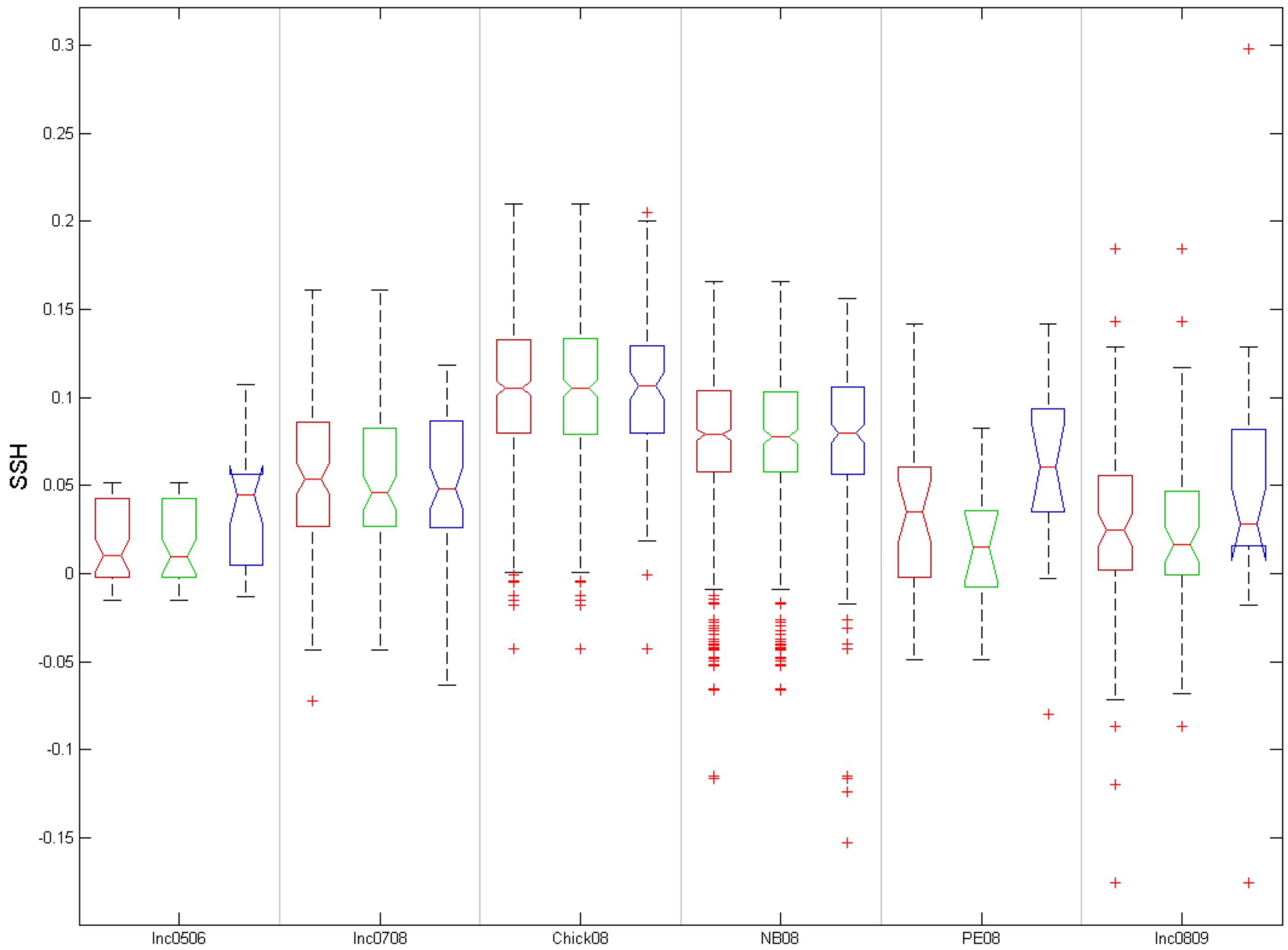
SSH
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Inc0506
Inc0708
Chick08
NB08
PE08
Inc0809

Figure 20

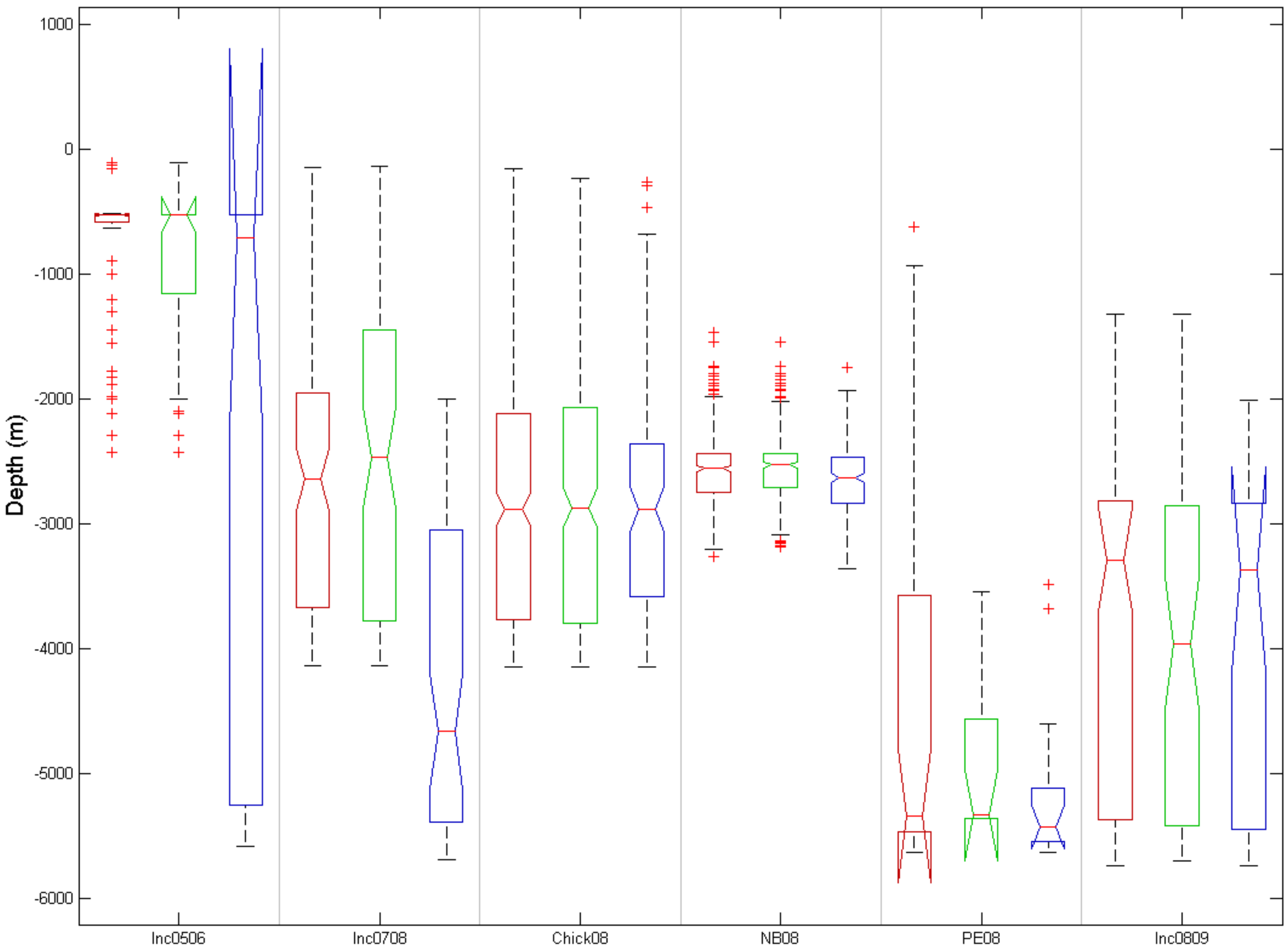
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Depth (m)
Inc0506
Inc0708
Chick08
NB08
PE08
Inc0809

Figure 21

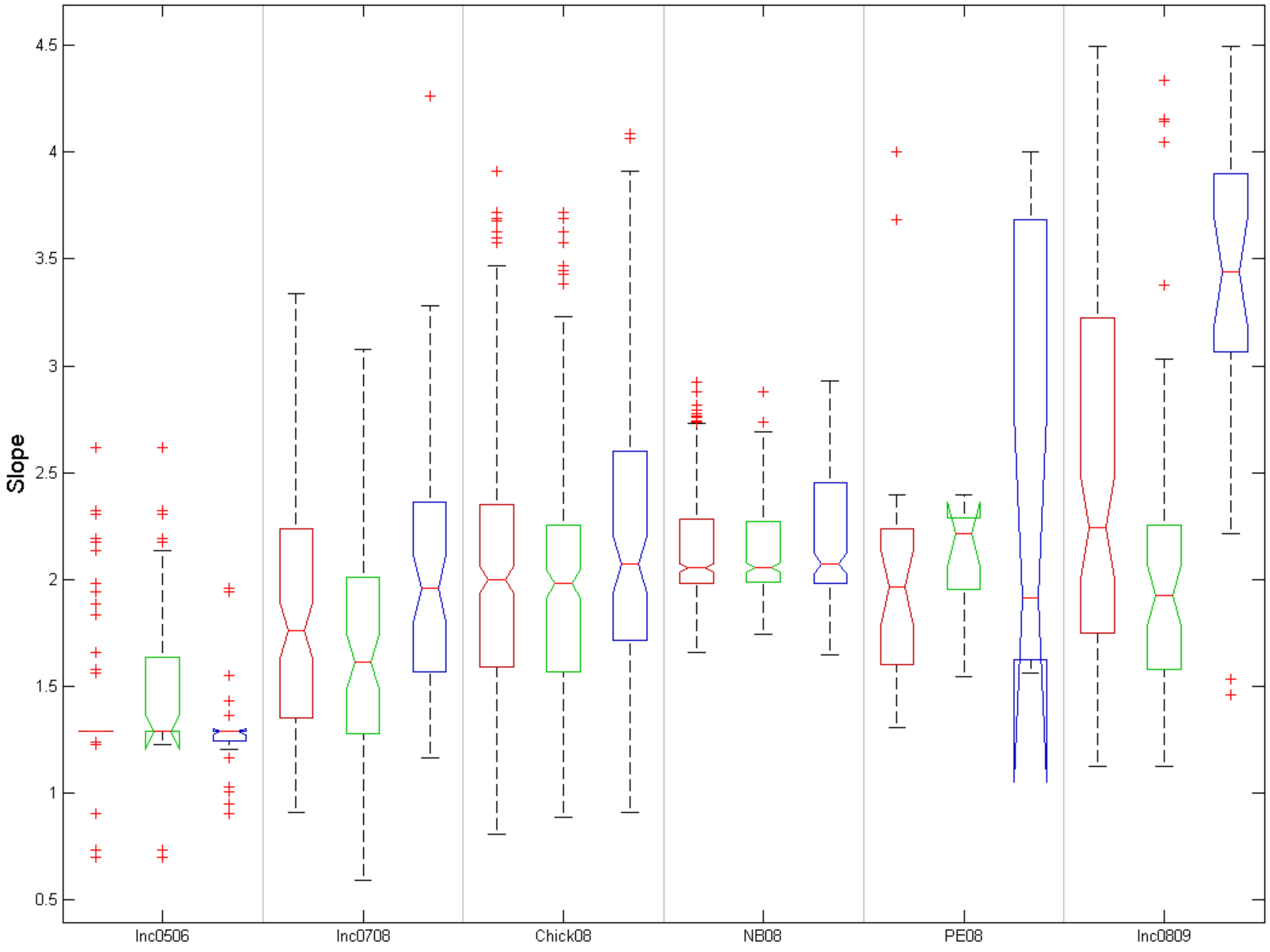
Slope
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Inc0506
Inc0708
Chick08
NB08
PE08
Inc0809

Table 1

| SEASON | | Logger type | Number of loggers deployed | | | | Number of loggers retrieved | Number of burrows | Breeding success | | No. of days loggers worn | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DEPLOYED | RETRIEVED | | Males | Females | Unknown | TOTAL | | | Logger burrows | All study burrows | Mean (± SEM) | Range |
| 2005/06 (December 05) | 2005/06 (February 06) | Lotek™ | 7 | 3 | 1 | 11 | 11 | 9 | 67% | 67% (05/06) | 45 ± 2 | 42-57 |
| 2007/08 (December 07) | 2007/08 (January 08) | | 7 | 1 | 0 | 8 | 8 | 8 | 75% | 77% (07/08) | 33 ± 1 | 30-35 |
| 2007/08 (December 07) | 2008/09 (December 08) | | 12 | 4 | 0 | 16 | 16[1] | 13 | 77% (07/08)<br>85% (08/09) | 77% (07/08)<br>76% (08/09) | 360 ± 1 | 354-369 |
| 2007/08 (December 07) | 2008/09 (February 09) | | 1 | 0 | 1 | 2 | 2[2] | 2 | 100% (07/08)<br>100% (08/09) | 77% (07/08)<br>76% (08/09) | 418 ± 3 | 415-421 |
| 2007/08 (December 07) | - | | 1 | 0 | 1 | 2 | 0 | 2 | - | - | - | - |
| 2008/09 (December 08) | 2008/09 (February 09) | | 5 | 1 | 2 | 8 | 8 | 8 | 88% | 76% (08/09) | 50 ± 2 | 44-62 |
| 2009/10 (December 09) | 2009/10 (February 10) | | 15 | 12 | 14 | 41 | 41 | 34 | 88% | 74% (09/10) | 50 ± 1 | 43-65 |
| 2009/10 (December 09) | - | | 1 | 2 | 1 | 4 | 0 | 3 | - | - | - | - |
| **TOTAL (Lotek™)** | | | **49** | **23** | **20** | **92** | **86 (93%)** | **79** | | | **113 ± 13** | **30-421** |
| 2008/09 (December 08) | 2009/10 (February 10) | BASTrak™ | 5 | 1 | 0 | 6 | 6[3] | 5 | 89% (08/09)<br>80% (09/10) | 76% (08/09)<br>74% (09/10) | 391 ± 13 | 358-420 |
| 2008/09 (December 08) | - | | 4 | 0 | 0 | 4 | 0 | 4 | - | - | - | - |
| **TOTAL (BASTrak™)** | | | **9** | **1** | **0** | **10** | **6 (60%)** | **9** | **-** | **-** | **391 ± 13** | **358-420** |
| 2008/09 (December 08) | 2008/09 (February 09) | SIRTrack™ | 2 | 2 | 1 | 5 | 5[4] | 5 | 80% | 76% (08/09) | 50 ± 2 | 44-55 |
| 2009/10 (January 10) | 2009/10 (February 10) | | 3 | 0 | 1 | 4 | 4 | 4 | 75% | 74% (09/10) | 16 ± 2 | 12-21 |
| **TOTAL (SIRTrack™)** | | | **5** | **2** | **2** | **9** | **9 (90%)** | **9** | **-** | **-** | **35 ± 6** | **12-55** |
| **TOTAL** | | | **63** | **26** | **22** | **111** | **101 (91%)** | **97** | | | | |

[1] All 16 birds recaptured, but one bird only had the attachment present (logger device had fallen off at sea).
[2] Both birds recaptured, but one bird only had the attachment present (logger device had fallen off at sea).
[3] All six birds recaptured, but one bird only had the attachment present (logger device had fallen off at sea).
[4] All five birds recaptured, but one bird had only some tape left (logger device had fallen off at sea).

Table 2

| No. | Track ID | Colony | Band | Burrow | Sex | Track start date | Track end date | Total days tracked | Number of points used in analyses (post filtering) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 36 | GBI | 27604* | 69 | M | 1 Dec. 2005 | 18 Jan. 2006 | 48 | 27 |
| 2 | 37 | GBI | 31460 | 65 | F | 1 Dec. 2005 | 4 Jan. 2006 | 34 | 28 |
| 3 | 38 | GBI | 25493* | 150 | M | 1 Dec. 2005 | 6 Jan. 2006 | 36 | 27 |
| 4 | 39 | GBI | 25511* | 102 | F | 3 Dec. 2005 | 30 Jan. 2006 | 58 | 35 |
| 5 | 40 | GBI | 31271* | 67 | M | 16 Dec. 2005 | 31 Dec. 2005 | 15 | 16 |
| 6 | 41 | GBI | 31023 | 41 | F | 3 Dec. 2005 | 20 Jan. 2006 | 48 | 30 |
| 7 | 42 | GBI | 30866 | 102 | M | 25 Dec. 2005 | 9 Jan. 2006 | 15 | 12 |
| 8 | 43 | GBI | 31242 | 71 | M | 23 Dec. 2005 | 13 Jan. 2006 | 21 | 19 |
| 9 | 44 | GBI | 27534* | 148 | M | 4 Dec. 2005 | 9 Jan. 2006 | 36 | 22 |
| 10 | 45 | GBI | 25460* | 146 | M | 2 Dec. 2005 | 11 Jan. 2006 | 40 | 21 |
| 11 | 46 | GBI | 30869 | 212 | M | 1 Dec. 2005 | 15 Jan. 2006 | 45 | 16 |
| 12 | 1 | GBI | 25494 | 137 | M | 22 Dec. 2007 | 15 Aug. 2008 | 237 | 154 |
| 13 | 2 | GBI | 34267 | 363 | M | 26 Dec. 2007 | 9 Jan. 2008 | 14 | 8 |
| 14 | 3 | GBI | 32920 | 271 | M | 31 Dec. 2007 | 7 May 2008 | 128 | 74 |
| 15 | 8 | GBI | 25447 | 135 | M | 21 Dec. 2007 | 4 Jan. 2008 | 14 | 13 |
| 16 | 9 | GBI | 33758 | 76 | M | 29 Dec. 2007 | 2 Feb. 2008 | 35 | 14 |
| 17 | 10 | GBI | 31271* | 67 | M | 24 Dec. 2007 | 26 Oct. 2008 | 307 | 95 |
| 18 | 12 | GBI | 29699 | 136 | M | 23 Dec. 2007 | 8 Jan. 2008 | 16 | 11 |
| 19 | 14 | GBI | 25471 | 150 | F | 13 Dec. 2007 | 26 Oct. 2008 | 318 | 179 |
| 20 | 15 | GBI | 33313 | 134 | F | 26 Dec. 2007 | 9 Jan. 2008 | 14 | 11 |
| 21 | 16 | GBI | 27534* | 148 | M | 21 Dec. 2007 | 14 Jan. 2008 | 24 | 11 |
| 22 | 18 | GBI | 25493* | 150 | M | 17 Dec. 2007 | 1 Dec. 2008 | 350 | 147 |
| 23 | 19 | GBI | 33492 | 265 | M | 30 Dec. 2007 | 12 Jan. 2008 | 13 | 10 |
| 24 | 22 | GBI | 25511* | 102 | F | 25 Dec. 2007 | 6 Jan. 2008 | 12 | 9 |
| 25 | 24 | GBI | 29693 | 74 | F | 15 Dec. 2007 | 8 Dec. 2008 | 359 | 209 |
| 26 | 26 | GBI | 30874* | 66 | M | 22 Dec. 2007 | 6 Jan. 2008 | 15 | 10 |
| 27 | 27 | GBI | 32005 | 68 | F | 17 Dec. 2007 | 14 Dec. 2008 | 363 | 203 |
| 28 | 28 | GBI | 25460* | 146 | M | 20 Dec. 2007 | 5 Dec. 2008 | 351 | 172 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 29 | 30 | GBI | 25404 | 80 | M | 22 Dec. 2007 | 3 Dec. 2008 | 347 | 197 |
| 30 | 33 | GBI | 27604* | 69 | M | 22 Dec. 2007 | 2 Jan. 2008 | 11 | 7 |
| 31 | 11 | GBI | 29700 | 165 | M | 3 Jan. 2008 | 19 June 2008 | 168 | 109 |
| 32 | 4 | GBI | 33306 | 138 | M | 12 Jan. 2008 | 25 Feb. 2008 | 44 | 22 |
| 33 | 21 | GBI | 28572 | 73 | M | 7 Jan. 2008 | 2 Dec. 2008 | 330 | 150 |
| 34 | 25 | GBI | 31991 | 217 | M | 3 Jan. 2008 | 7 Dec. 2008 | 339 | 136 |
| 35 | 32 | GBI | 31974 | 74 | M | 4 Jan. 2008 | 20 Nov. 2008 | 321 | 202 |
| 36 | 13 | GBI | 25673 | 103 | M | 30 Dec. 2008 | 10 Jan. 2009 | 11 | 9 |
| 37 | 17 | GBI | 29699 | 136 | M | 16 Dec. 2008 | 31 Dec. 2008 | 15 | 5 |
| 38 | 20 | GBI | 36175 | 144 | U | 17 Dec. 2008 | 25 Dec. 2008 | 8 | 6 |
| 39 | 23 | GBI | 30874* | 66 | M | 23 Dec. 2008 | 25 Jan. 2009 | 33 | 15 |
| 40 | 34 | GBI | 14018 | 361 | M | 17 Dec. 2008 | 26 Jan. 2009 | 40 | 17 |
| 41 | 5 | LBI | 27701 | 32 | M | 16 Dec. 2007 | 16 June 2008 | 183 | 93 |
| 42 | 6 | LBI | 36149 | 36 | F | 19 Jan. 2008 | 12 Nov. 2008 | 298 | 181 |
| 43 | 7 | LBI | 36753 | 10 | U | 18 Dec. 2008 | 30 Dec. 2008 | 12 | 11 |
| 44 | 29 | LBI | 36105 | 27 | F | 21 Dec. 2007 | 1 Dec. 2008 | 346 | 190 |
| 45 | 31 | LBI | 36103 | 21 | U | 16 Dec. 2007 | 30 Dec. 2007 | 14 | 10 |
| 46 | 35 | LBI | 23005 | 15 | F | 9 Dec. 2007 | 22 Feb. 2008 | 75 | 18 |
| | | | | | | | **TOTAL** | **5561** | **2961** |

Table 3

| Phase | | Start date | End date |
|---|---|---|---|
| Breeding | Pre-egg laying | 1 October | 15 November |
| | Incubation | 16 November | 31 January |
| | Guard & chick rearing | 1 February | 15 May |
| Non-breeding | | 16 May | 30 September |

Table 4

| Stage | Date (First point) | Date (Last point) | Number of points | SST NaNs | Chl-*a* NaNs | SSH NaNs |
|---|---|---|---|---|---|---|
| Incubation 05-06 | 1 Dec. 2005 | 30 Jan. 2006 | | | | |
| Total | | | 253 | 0 | 1 | 0 |
| Males | | | 160 | 0 | 1 | 0 |
| Females | | | 93 | 0 | 0 | 0 |
| Incubation 07-08 | 9 Dec. 2007 | 31 Jan. 2008 | | | | |
| Total | | | 328 | 0 | 220 | 0 |
| Males | | | 215 | 0 | 153 | 0 |
| Females | | | 103 | 0 | 66 | 0 |
| Unknown | | | 10 | 0 | 1 | 0 |
| Chick rearing 08 | 1 Feb. 2008 | 22 May 2008 | | | | |
| Total | | | 976 | 4 | 300 | 0 |
| Males | | | 649 | 3 | 189 | 0 |
| Females | | | 327 | 1 | 111 | 0 |
| Migration East | 2 Mar. 2008 | 5 Jun. 2008 | | | | |
| Total | | | 199 | 0 | 41 | 0 |
| Males | | | 110 | 0 | 27 | 0 |
| Females | | | 89 | 0 | 14 | 0 |
| Non-breeding 08 | 29 Mar. 2008 | 26 Oct. 2008 | | | | |
| Total | | | 1064 | 26 | 384 | 13 |
| Males | | | 599 | 22 | 221 | 12 |
| Females | | | 465 | 4 | 163 | 1 |
| Migration West | 3 Aug. 2008 | 15 Nov. 2008 | | | | |
| Total | | | 166 | 0 | 0 | 0 |
| Males | | | 102 | 0 | 0 | 0 |
| Females | | | 64 | 0 | 0 | 0 |
| Pre-egg laying 08 | 24 Oct. 2008 | 15 Nov. 2008 | | | | |
| Total | | | 168 | 0 | 8 | 0 |
| Males | | | 104 | 0 | 7 | 0 |
| Females | | | 64 | 0 | 1 | 0 |
| Incubation 08-09 | 16 Nov. 2008 | 26 Jan. 2009 | | | | |
| Total | | | 161 | 0 | 3 | 0 |
| Males | | | 102 | 0 | 1 | 0 |
| Females | | | 42 | 0 | 2 | 0 |
| Unknown | | | 17 | 0 | 0 | 0 |

Table 5

| SEASON | | Number of loggers deployed | | | | Number of loggers retrieved | Tracking results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Complete Tracks | No tracks | Partial Tracks (month of failure) | | | | | | |
| DEPLOYED | RETRIEVED | Males | Females | Unknown | TOTAL | | | | Jan. 08 | Feb. 08 | May 08 | Jun. 08 | Aug. 08 | Oct. 08 | Dec. 08 |
| 2005/06 (December 05) | 2005/06 (February 06) | 7 | 3 | 1 | 11 | 11 | 11 | - | - | - | - | - | - | - | - |
| 2007/08 (December 07) | 2007/08 (January 08) | 7 | 1 | 0 | 8 | 8 | 8 | - | - | - | - | - | - | - | - |
| 2007/08 (December 07) | 2008/09 (December 08) | 12 | 4 | 0 | 16 | 16 | 8 | 1[5] | 1 | 2 | 1 | 1 | 1 | 1 | - |
| 2007/08 (December 07) | 2008/09 (February 09) | 1 | 0 | 1 | 2 | 2 | - | 1[6] | - | - | - | - | - | 1 | - |
| 2007/08 (December 07) | - | 1 | 0 | 1 | 2 | 0 | - | - | - | - | - | - | - | - | - |
| 2008/09 (December 08) | 2008/09 (February 09) | 5 | 1 | 2 | 8 | 8 | 3 | 3 | - | - | - | - | - | - | 2 |
| **TOTAL** | | **33** | **9** | **5** | **47** | **45 (96%)** | **30 (67%)** | **5 (11%)** | **1** | **2** | **1** | **1** | **1** | **2** | **2** |
| | | | | | | | | | **10 (22%)** | | | | | | |

[5] Bird recaptured, but only had the attachment present (logger device had fallen off at sea)
[6] Bird recaptured, but only had the attachment present (logger device had fallen off at sea)

Table 6

| Breeding Phase | Area of 95% contour ($km^2$) | Area of 50% contour ($km^2$) |
|---|---|---|
| Non-breeding 2008 | 1335915 | 240125 |
| Chick Rearing 2008 | 4003367 | 693614 |
| Pre-egg 2008 | 6165858 | 770002 |
| Incubation 2005/06 | 6309113 | 298967 |
| Incubation 2007/08 | 9829410 | 1186131 |
| Incubation 2008/09 | 10267689 | 1993453 |

Table 7

| | Inc. 2005/06 | Inc. 2007/08 | Chick 2008 | Non-breeding 2008 | Pre-egg 2008 | Inc. 2008/09 |
|---|---|---|---|---|---|---|
| SST | **17.62 (<0.001)** | 3.61 (0.6) | **5.27 (0.02)** | **17.82 (<0.001)** | **15.43 (<0.001)** | **8.94 (0.003)** |
| CHLA | **70.77 (<0.001)** | **7.27 (0.008)** | 5 (0.3) | **26.46 (<0.001)** | 1.02 (0.32) | 2.74 (0.10) |
| SSH | **8.23 (0.004)** | 2.09 (0.15) | **30.31 (<0.001)** | **12.45 (<0.001)** | 1.03 (0.31) | 1.68 (0.20) |
| Depth | **251.11 (<0.001)** | **56.02 (<0.001)** | **11.22 (<0.001)** | **438.13 (<0.001)** | **10.14 (0.002)** | 0.34 (0.56) |
| Slope | **14.14 (<0.001)** | **5.85 (0.02)** | **5.58 (0.02)** | **8.89 (0.003)** | **6.37 (0.01)** | **14.98 (< 0.001)** |

Table 8

| | Inc. 2005/06 | Inc. 2007/08 | Chick 2008 | Non-breeding 2008 | Pre-egg 2008 | Inc. 2008/09 |
|---|---|---|---|---|---|---|
| SST | **4.94 (0.03)** | **4.38 (0.04)** | 2.2 (0.14) | 2.17 (0.14) | 3.02 (0.09) | 0.47 (0.49) |
| CHLA | 0.81 (0.37) | **20.33 (<0.001)** | 1.8 (0.18) | 3.62 (0.06) | 0 (0.99) | 2.39 (0.13) |
| SSH | **10.49 (0.002)** | 0.48 (0.49) | 0 (0.98) | 0.48 (0.49) | **5.22 (0.03)** | 2.85 (0.10) |
| Depth | **21.1 (<0.001)** | **84.05 (<0.001)** | 0.02 (0.88) | **15.72 (<0.001)** | 0.49 (0.49) | 0.07 (0.79) |
| Slope | 3.63 (0.06) | **13.47 (<0.001)** | **6.71 (0.01)** | **5.92 (0.02)** | 1.05 (0.32) | **51.15 (<0.001)** |

Table 9

| | **CONTOUR** | **GENDER** |
|---|---|---|
| **Incubation 2005/06** | | |
| SST | *** (50% COOLER) | * (FEMALES COOLER) |
| CHLA | *** (50% >) | |
| SSH | ** (50% <) | ** (FEMALES > SSH) |
| DEPTH | *** (50% SHALLOWER) | *** (MALE SHALLOWER) |
| SLOPE | *** (50 % LESS SLOPE) | |
| | | |
| **Incubation 2007/08** | | |
| SST | | * (MALES COOLER) |
| CHLA | ** (50% >) | *** (MALE > CHLA) |
| SSH | | |
| DEPTH | *** (50% SHALLOWER) | *** (MALE SHALLOWER) |
| SLOPE | * (50 % LESS SLOPE) | *** (FEMALES > SLOPE) |
| | | |
| **Chick 2008** | | |
| SST | * (50% WARMER) | |
| CHLA | | |
| SSH | *** (50% HIGHER SSH) | |
| DEPTH | *** (50% DEEPER) | |
| SLOPE | * (50 % LESS SLOPE) | * (FEMALES > SLOPE) |
| | | |
| **Non-breeding 2008** | | |
| SST | *** (50% WARMER) | |
| CHLA | *** (50% HIGHER CHLA) | |
| SSH | * (50% HIGHER SSH) | |
| DEPTH | *** (50% SHALLOWER) | *** (MALE SHALLOWER) |
| SLOPE | ** (50 % MORE SLOPE) | * (FEMALES > SLOPE) |
| | | |
| **Pre-Egg 2008** | | |
| SST | *** (50% COOLER) | |
| CHLA | | |
| SSH | | * (FEMALES > SSH) |
| DEPTH | ** (50% DEEPER) | |
| SLOPE | * (50% < SLOPE) | |
| | | |
| **Incubation 2008/09** | | |
| SST | ** (50 % COOLER) | |
| CHLA | | |
| SSH | | |
| DEPTH | | |
| SLOPE | *** (50% > SLOPE) | *** (FEMALES > SLOPE) |