Estimating Exposure of Vulnerable Seabird Populations to Offshore Light Pollution

DANIEL PETTERSON, Victoria University of Wellington

Many seabird species are active during the night and artificial light from sources such as fishing vessels have been shown to affect their survival. We use information from light-level loggers (GLS) to estimate the location and frequency of these events among a variety of species native to Aotearoa New Zealand. 179 seabirds from 7 species were tracked between October 2008 and November 2019 using light-based geolocators. There were notable differences in rates of light exposure between species with more events recorded in pelagic areas. Light exposure had a significant effect on behavioural patterns in some species while having little effect on others.

Keywords: GLS, Geolocation by light, ALAN, probGLS, Broad-billed Prion, Fairy Prion, Chatham Island Taiko, Chatham Petrel, Whenua Hou Diving Petrel, Sooty Shearwater, Flesh-footed Shearwater

INTRODUCTION

Exposure to artificial light at night (ALAN) has been shown to be a threat to nocturnally migrating birds [Longcore and Rich, 2004]. Ambient light impacts the migration and foraging behaviours of many species of marine birds as well as their ability to correctly orient themselves [Montevecchi, 2006, Bruderer et al., 1999]. The resulting disorientation significantly increases the risk of a collision between the bird and nearby objects [Merkel and Johansen, 2011, Black, 2005]. Many seabirds species, including the Broad-billed Prion tracked in this study, have been shown to their survival negatively impacted by night time light exposure [Glass and Ryan, 2013].

Research regarding ALAN events has previously been used to inform measures to mitigate the danger posed by light pollution to birds from fishing and other commercial vessels. In order to understand which species are most at risk we must have accurate information regarding the location and timing of ALAN events. Widespread methods of tracking larger animals such as the use of GPS are often not suitable for use with smaller birds due to safety concerns stemming from the additional weight [Severson et al., 2019]. Miniaturized GPS units do exist that offer a safer alternative but due to battery constraints are only capable of recording their location a few times per deployment so tracking on a fine temporal scale is not possible. The development of global location sensors (GLS) has brought an alternative way to track species for which a satellite based tracker would have been unsuitable [Wilson, 1992]. GLS tags can record light intensity, conductivity and in some cases, temperature data.

Using the features of the light data we are able to estimate the timing of sunrise and sunset - herein referred to as twilight events - using a threshold method as described by Ekstrom et al. [2004]. Light intensities above or below a set threshold signal the occurrence of a twilight event [Hill and Braun, 2001]. The threshold method is shown to be robust but has notable difficulties near the equator [Ekstrom et al., 2004] and provides no information that can be used to track species in periods of polar night or polar day. As the Earth moves around the Sun, the length of the day (defined as the time between sunrise and sunset) changes. The extent to which it changes depends on the latitude at which the recording was made. Similarly, longitude can be estimated based on the time at which solar noon and midnight - the midpoint between each set of twilight events - occurs.

The accuracy of location estimates can be enhanced by the inclusion of conductivity and temperature data as well as species-specific parameters relating to their behaviour. Conductivity readings are used to determine if a bird is immersed in water or airborne. The movement speed of a bird on or in water is lower than when it is airborne, enabling us to define two speed distributions and filter potential locations based on their distance from the previous location and the proportion of time spent in each state. Temperature data is used to determine the local sea surface temperature that when cross-referenced against data from satellite-based temperature recording devices has been shown to yield more probable flight paths with lower variance than the usage of light data alone [Nielsen et al., 2006].

METHODOLOGY

Study species and logger deployment

A total of 179 seabirds across 7 species were fit with light-level geolocators (GLS) between October 2008 and November 2019. All species have colonies located in Aotearoa New Zealand (Fig. 1). The loggers used were a range of models from Migrate Technology, British Antarctic Survey (BAS), and Biotrack. In many cases, a variety of loggers were used within the same species. Individual birds recorded data over periods ranging from 1 to 1084 days and the logger data was downloaded. In some cases the loggers failed prematurely which resulted in shorter than anticipated recording times. Some birds, particularly the Broad-billed Prions and Fairy Prions were re-equipped with loggers and data was gathered over multiple shorter periods.

Species	Abbreviation	Colony Locations
Broad-billed Prion	BBP	Rangatira Island
Chatham Petrel	CP	Rangatira Island
Chatham Island Taiko	CT	Tuku Valley
Fairy Prion	FP	St Clair
Whenua Hou Diving Petrel	WHDP	Whenua Hou
Flesh-footed Shearwater	FFS	Kauwahaia Island
		Lady Alice Island
Sooty Shearwater	SS	Kauwahaia Island
		Mana Island
		Rangatira Island

Table 1: Location of Seabird Colonies and Abbreviations of Common Names.

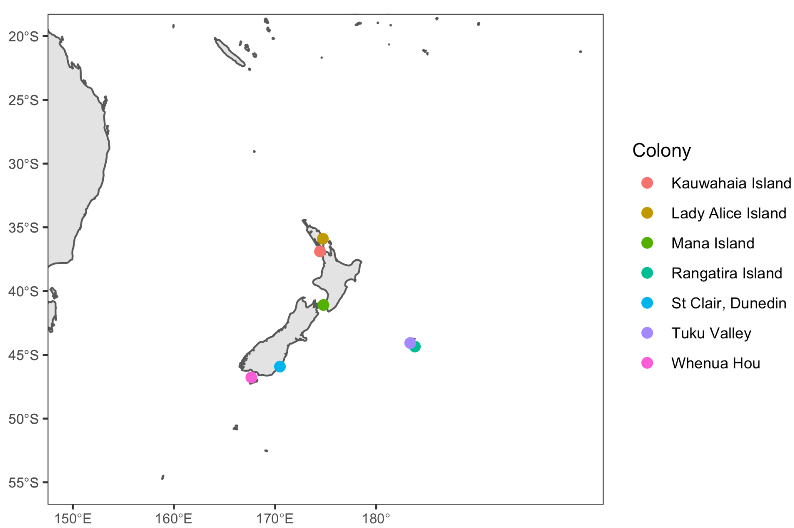

Figure 1: Location of Seabird Colonies

Processing of GLS data

Loggers sampled light every 3 seconds, and recorded the maximum value in each 5 or 10 minute interval. The manufacturer of the logger determined how light values were recorded. Migrate Technology loggers recorded light levels in lux, whereas BAS and Biotrack loggers recorded light values on a constructed scale between 0 and 64 and are limited to dim light levels. In addition to light levels, loggers also measured conductivity and determined if a logger was wet or dry every 3 or 30 seconds. The number of wet readings was summed for every 5 or 10 minute interval giving a maximum value of either 20 or 200. Conductivity data was rescaled to (0,1) to ensure comparable values across loggers. Some BAS (mk7, mk15) and Migrate Technology (c65_super) loggers are capable of recording temperatures while wet which can be used to estimate local sea-surface temperatures.

Using the time series of light recordings, probable times for twilight events were estimated using the threshold method. Suggested twilight times were generated using the `twilightCalc` function from the `Geolight` package [Lisovski et al., 2012]. and manually filtered in order to minimise errors caused by shading or artificial light events. Once the most suitable timing of the twilight events is established we are able to estimate up to two locations per full day cycle using the `probGLS::prob_algorithm` function [Merkel et al., 2016] in R [R Core Team, 2020]. The `prob_algorithm` function is an iterative forward-step selection probability algorithm that generates a cloud of potential locations and the median value at each step is taken as the most likely location of the bird.

Temperature data was recorded by some logger models and was used to enhance the accuracy of the location estimates by comparing the daily median water temperature encountered by each bird to the daily mean satellite-derived sea-surface temperature (SST) extracted from the NOAA (National Oceanic and Atmospheric Administration) high-resolution dataset. The median temperature was used in place of the mean to avoid inflated temperature recordings caused by the body heat of the bird [Fischer et al., 2021].

To avoid the incorrect classification of daylight as light originating from artificial sources we make a few corrections. Firstly, all light observations 60 minutes either side of each twilight event were removed as are those between non-consecutive twilight events. Secondly, recordings within 30 days either side of the southern summer solstice were removed to avoid instances of polar day being misattributed to artificial light sources. For species crossing the equator like Shearwaters, records within 30 days either side of the September equinox are removed, The same measure is taken for the other species but only records 20 days either side of the equinox are removed. During an equinox the length of day and night are equivalent which poses an issue for calculating the latitude and the resulting estimation is much less reliable than during other times of the year. The final correction was to remove observations that occurred between evening twilight events that were more than 26 hours apart. This serves to avoid recording of natural light in the event that a twilight event is removed if it deems the timing too improbable.

Location filters

A speed filter is applied where locations outside of a given distance from the previously calculated location are filtered out. The conductivity data shows the proportion of time a bird spends in water relative to flying. Average and maximum flight speeds are species-specific parameters but when in water a bird is assumed to travel at approximately the speed of the ocean currents. Therefore the higher the proportion of time spent in the water, the lower the distance that the bird has likely traveled since the last estimated point.

Determining ALAN events

ALAN events are defined as all light recordings above a given threshold that occur between the sunset and sunrise of a single day cycle. The threshold varies based on the type of logger which was used. Loggers were split into three groups, the Biotrack-high group consisted of Biotrack mk3006 and mk 3005, and BAS mk7, mk10, mk15, and mk19 loggers and all light readings equal or greater than 10 were defined as originating from artificial light sources as done by Krüger et al. 2017 [Krüger et al., 2017]. Biotrack models 4093 and 4083 and BAS mk13, mk14 and, mk18 made up the Biotrack-low group for which a threshold light intensity level of 5 was used in order to have have comparable data in terms of number and duration of encounters [Dupuis et al., 2021]. The final group was comprised of loggers manufactured by Migrate Technology, specifically the C65-SUPER and W65A9-SEA models. Migrate Technology loggers measure intensity in lux instead of a set of non-linear levels as with the others. A threshold of 20 lux was used to trigger recognition of an ALAN event. Light recordings above these levels were grouped if they occurred consecutively and each grouping constitutes a singular event.

Defining behaviour

Conductivity data was used to determine the activity that a bird was engaged in at a given point in time. The loggers record whether they are wet or dry, as determined by conductivity, every 3 seconds and the number of recordings over an interval determine the behaviour that a bird was engaged in. If less than 5% of recordings over and interval where recorded as wet then the bird is assumed to be in flight, wet readings for 95% or greater of the interval denote swimming and all other readings are associated as foraging behaviour where a bird will alternate between being airborne and in water [Mattern et al., 2015]. Behavioural categorisation was applied in the same manner across all species.

RESULTS

Artificial light events were detected at least once by 69 of the 179 birds that logger data was retrieved from. The temporal and geographic distribution of exposure events differs between species. This is to be expected as the overlap of migration patterns can be small between some species and certain areas are more densely populated by artificial light sources such as fishing vessels than others.

Species level summaries

Some species are more frequently exposed to artificial light than others. Of the 24 Whenua Hou Diving Petrels, only 18% had any night time light exposure events. This contrasts heavily with the Fairy Prions of which 57% experienced light exposure. In this case the difference is largely due to the proximity to population centres and areas of high vessel traffic.

Species	FP	BBP	FFS	SSH	CP	WHDP	CT
Total birds	14	21	47	72	22	22	27
Birds with detections	8	9	17	24	4	4	3
% with detections	57	43	36	33	18	18	11
Average # of nights recorded	280	140	402	177	247	309	264
# of light events	19	33	70	75	19	7	4
Median duration (mins)	5	10	30	30	40	30	25

Table 2: Summary of deployments and encounters per species.

The median duration of light events also differs considerably with those that impact Chatham Petrels being eight times longer than those that Fairy Prions are exposed to. It should be noted that as the readings are the maximum light intensity observed over an interval, exposure may not be continuous.

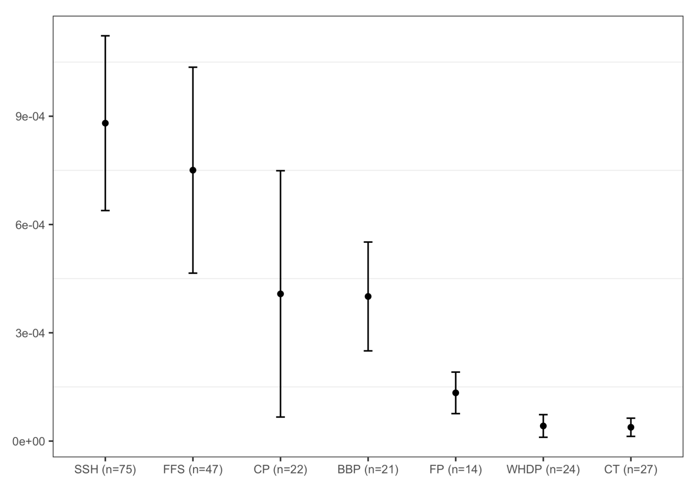

Figure 2: Proportion of recorded time with light exposure by species.

There is significant variation in the proportion of recorded time that light events were detected in some species. Of the species tracked, Chatham Island Taikos, Fairy Prions and Whenua Hou Diving Petrels have the lowest average amount of time exposed to artificial light at night.

Geographical Distribution of ALAN events by species

While each species has colonies in Aotearoa New Zealand, the areas in which they are active can differ greatly over time. There are a large proportion of events that occur near coastal areas and major shipping lanes.

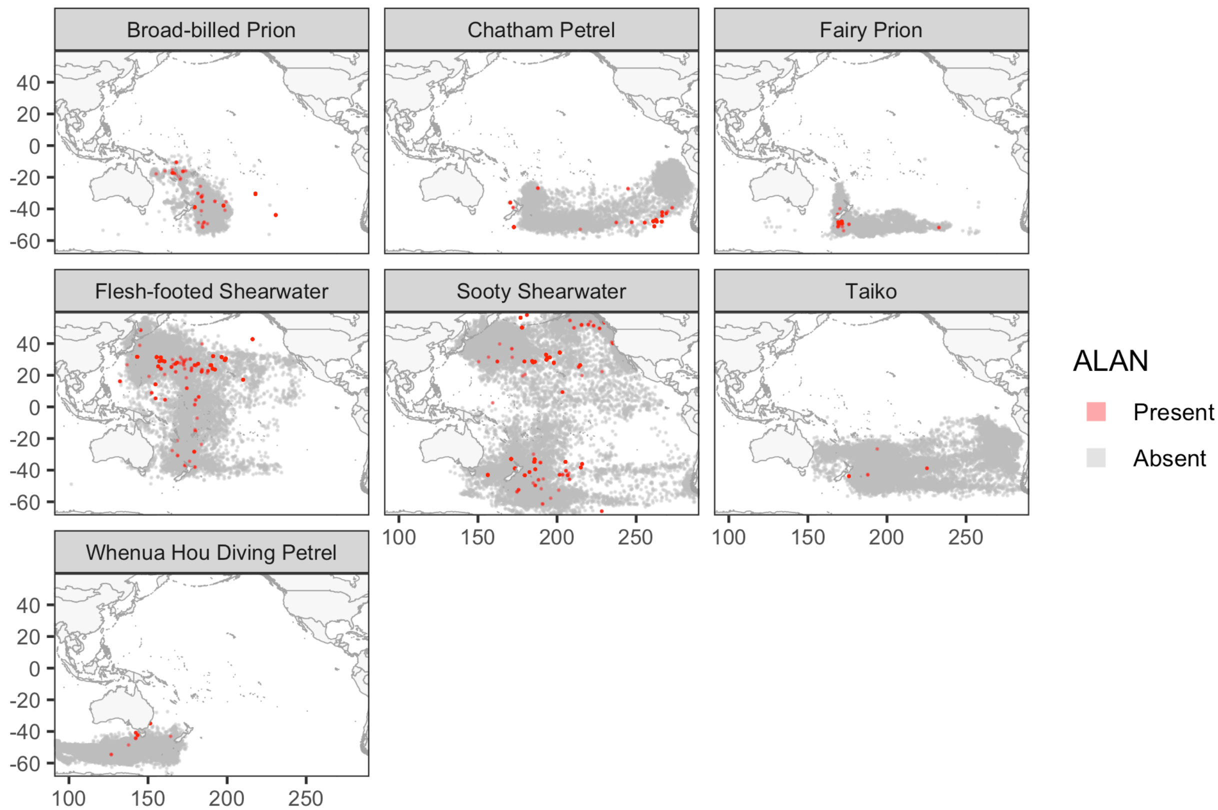

Figure 3: Estimated locations and prevalence of light events.

Flesh-footed and Sooty Shearwaters have the largest range of all the species and also accounted for the vast majority of ALAN event recordings. This is partially due to the number that were tracked and the amount of nights we have recorded data for. The flight paths of the Taiko and Whenua Hou Diving Petrel, while also covering a large region, suffered relatively few light exposure events in comparison. The geographic distribution of light exposure events suggests that exposure is more frequent in the northern Pacific Ocean and near the coasts of the south-eastern portions of New Zealand and Australia.

Temporal Distribution of Events

ALAN events are not evenly distributed across time or birds. We see that many birds can go their entire deployments without light exposure but others can experience it on multiple consecutive days. Recordings of light values may have been removed for a range of reasons. Systematic removals such as the removal of recordings around an equinox due to unreliable location estimates may skew results. The Shearwaters, for example, are known to spend the time over that period largely in the northern hemisphere so it is likely that the frequency of light exposure events in that region are underestimated as a result of removing these records.

Figure 4: Deployment period and distribution of ALAN events for seven study species.

Bird Activity During Light Detections

Light exposure among seabirds is associated with behavioural changes and disorientation. Disorientation is associated with behaviour that resembles foraging in that it can cause the bird to struggle to remain airborne. Disorientation via light is one of the major causes of deck strike. We see that in some species, particularly the Sooty Shearwater, Flesh-footed Shearwater and Broad-billed Prion, light exposure is associated with a significantly higher proportion of time spent alternating between being airborne and being in the water.

Activity	Light Exposure	BBP	CP	CT	FFS	FP	SSH	WHDP
Swimming	Light Event	0.10	0.44	0.75	0.18	0.03	0.22	0.85
Flying	Light Event	0.23	0.30	0.08	0.33	0.82	0.20	0.00
Foraging	Light Event	0.67	0.26	0.17	0.48	0.15	0.58	0.15
Swimming	No Light Event	0.38	0.29	0.39	0.43	0.22	0.77	0.77
Flying	No Light Event	0.38	0.47	0.47	0.20	0.54	0.14	0.09
Foraging	No Light Event	0.25	0.24	0.14	0.37	0.25	0.09	0.14

Table 3: Proportion of time spent across activities.

DISCUSSION

This study provides insight into the geographic and temporal distribution of ALAN events at sea on a variety of species native to Aotearoa New Zealand. Species that are active over a larger area such as the Sooty and Flesh-footed Shearwater have a greater proportion of their night time exposed to artificial light sources than those with smaller ranges or that tend to be active in areas with little fishing activity such as the Whenua Hou Diving Petrel.

Previous studies have demonstrated the utility of using light-level loggers in determining not only migration patterns of seabirds but also detecting when incidents of night time light exposure occur [Krüger et al., 2017, Dupuis et al., 2021]. Due to the measure that we are trying to observe, the prevalence of ALAN events, being derived from the same data source that we use to estimate where these events occur there is some interplay that we need to be considerate of. Any errors in the process of determining the twilight times have the potential to not only lead to an incorrect location estimate but may also introduce false positives, light recordings that are the result of natural sunlight rather than artificial sources. If a location estimate was the only concern then we could rely on semi-automated methods of twilight event estimation but due to the predisposition of the function used to calculate twilight events, `GeoLight::TwilightCalc`, to mark any instances passing the threshold, regardless of intensity and duration, as twilight events if they are further away than the last expected twilight times can lead to inaccurate designations that then have a flow on effect for future twilight calculations and thus have a high chance of biasing the result in these kind of studies. These issues are commonly the result of prolonged shading of the logger but may also be caused by instances of polar night or polar day. Shading tends to occur when the birds are in burrows or the logger is improperly placed.

Limitations of GLS Data

Geolocation by light allows the tracking of a variety of species for which it would otherwise prove difficult to follow through their migration periods. GLS loggers are small, light, and present minimal drag or wing loading. They are generally considered safe and very affordable but light-level geolocation is inherently prone to coarse spatial accuracy, particularly for estimates of latitude which are generally considered to become less accurate under increasingly equatorial solar profiles; that is, either nearer the Equator or solar equinox when there is a shallower difference in length between day and night. In order to compensate for issues caused by a solar equinox, the algorithm samples latitude values from a uniform distribution between the upper and lower extremes of the user-defined boundary box [Merkel et al., 2016]. Thus we can expect that, particularly in the absence of sea surface temperature data, the accuracy of the location estimate suffers. As each location estimate is influenced by the median latitude and longitude values of the previous step, the error in the location estimates may compound over this period. For this reason all recordings over the periods of surrounding the southern equinox have been removed from this data. Many studies quote the location accuracy reported in the initial study where Merkel et al. (2016) found that the mean estimated distance from GPS recordings on double-tagged birds was 145km during the equinox period. Recent research on a variety of species has shown that the error may be significantly larger. [Halpin et al., 2021] reported that the probGLS algorithm had a mean error of 304km and that the error increases both around the equinox and nearer to the equator. As such it is ill-advised to assume a universal accuracy error and to take these factors into account for estimates with more equatorial solar profiles.

Shading is a major issue in deriving accurate location estimates. Shading during sunrise and sunset can lead to inaccurate estimates for twilight times which can then negatively impact the accuracy of location estimates. The `probGLS` algorithm accounts for this somewhat by assuming a distribution of the error in twilight time estimates (Figure 5) but can not completely control for extended periods of shading. In order to prevent issues related to this we have not assigned twilight events to unlikely daylight periods so as to not bias the location estimates. This has the effect of discarding light data from dates where shading was significant and the impact of this can be seen in Figure 4. Some species were more affected than others and this could partially be attributed to the type of logger but may also be related to logger placement and bird physiology. We saw a disproportionately high loss of data due to shading in the Broad-billed Prions, Taikos, Flesh-footed and Sooty Shearwaters and relatively little loss amongst the Fairy Prions and Whenua Hou Diving Petrels.

The method used in this report allows for up to two location estimates per 24 hour period with any artificial light event attributed to the last estimated location. Among species that travel great distances in a short span of time this may be misleading if the light exposure occurs nearer to the time of the next location estimate. Depending on the purpose it may be beneficial to use linear interpolation between two locations to achieve a better estimate of location at a given time point. Linear interpolation fails to account for the curvature of the earth but over short distances the error is small on the scale of the relative inaccuracy of the location estimates derived from GLS loggers.

Filtering Methods

Species that live further from the equator have larger differences between day and night length. During certain times of the year they may have very short night periods and therefore the removal of recordings one hour post-dusk and pre-dawn may result in only a small window being recorded each night. The 60 minute filter is designed to minimise the misclassification of daylight as artificial light. Estimated twilight times are based on the location determined by the algorith and not the manually defined twilight events that are chosen based on light data patterns. We assume that twilight time error for open bird habitats (Figure 5) is log normal distributed with 90% of error being within 30 minutes. The danger in reducing the time filter is that there are relatively few ALAN events compared to the number of false positives introduced with even a minor reduction in the filter length. A viable alternative would be to apply shorter filter but also remove any consecutive recordings above the night time level the originate from estimated dusk or end at estimated dawn.

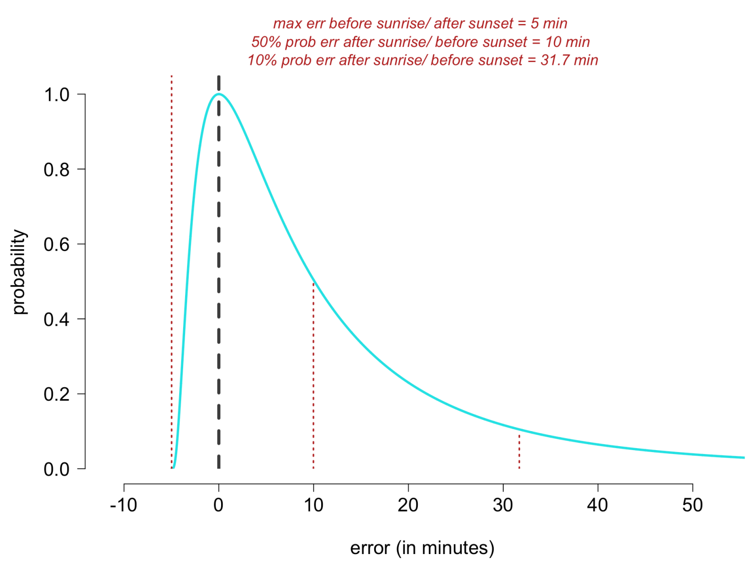

Figure 5: Distribution of twilight error for open habitat birds.

Temperature Data

As the addition of temperature data has been shown to increase the accuracy of location estimates, this has a flow on effect as the estimated twilight times tend to be more accurate [Nielsen et al., 2006, Merkel et al., 2016]. As a result, loggers that also record temperature data tend to yield a smaller number of false positive results given the same filtering parameters.

Impact of Polar Day

The period around each solstice is associated with an increase ambient light intensity near the respective pole. This can surpass the threshold which defines an event resulting in a large number of false positive readings over this period. One method of controlling for this would be to increase the threshold over this period but that leads to a reduced ability to detect real ALAN events. Alternatively one could, as we have done, remove all recordings within this period but this leads to a large proportion of data being lost. A more effective solution, especially in cases where not all birds being observed are within the affected zone, would be to only remove recordings during these periods if a bird was estimated to be at an latitude where increased ambient light intensity is present.

The Effect of the Loess Filter

The loess filter works by removing twilight times that are too far from a local polynomial regression fitting process. The flexibility of the line varies using the k parameter. Larger k values allow for a higher degree of variation between neighboring events and are appropriate for species such as Sooty and Flesh-footed Shearwaters due to the increased likelihood of bouts of long distance migration that can lead to larger shifts in inter-twilight duration. Conversely, a smaller k value is useful in cases where older loggers such as the Mk 4093 or Mk 3006 are used or the birds are expected to be near significant amounts of artificial lights such as the Fairy Prion. In these cases we see a higher number of erroneous twilight time calculations which impede our ability to determine both location and whether a light reading occurs during the day or night. While this minimises the chance of false positives, the removal of a large proportion of unlikely twilight event times also leads to a loss of information about potential ALAN events. The risk of information loss is not uniformly distributed across the deployment period. This imbalance is caused by issues inherent in estimating twilight events following extended periods of either continual light exposure or a complete lack of it. This filter can cause issues when it removes an event indicating sundown but not the corresponding sunrise. If this occurs then the entire next day may be defined as artificial light. The use of the loess filter is not advised for use when trying to detect night time light events.

Closing Remarks

This served as a useful exercise in quantifying the prevalence of ALAN events at sea along the migratory routes of a variety of rare and endangered species. Light-level loggers not only allow for safe tracking of a large variety of species over long time periods but, by their very nature, provide light intensity data which can be used to estimate the frequency and impact of night time light events. It is necessary to understand the limitations inherent with this method of tracking and how those limitations impact both the range of time that ALAN events can be reliably detected and the accuracy of the location estimates provided. The companion Shiny app can be found at https://docnewzealand.shinyapps.io/seabird_ALAN/.

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