Agreement on the Conservation of Albatrosses and Petrels

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Using existing GPS tracking data to quantify flight parameters of albatrosses and petrels for offshore windfarm risk assessments - simple GPS data is not enough

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SUMMARY

Offshore wind farms (OWFs) are expected in Australasia in the coming decade. OWFs have the potential to impact seabirds in several ways, particularly through habitat loss and collision fatalities. To assess collision risk, information on bird flight parameters, including flight height, nocturnal flight activity, and flight speed, is needed. For many Southern Hemisphere species, these data are lacking. Here, we opportunistically use previously collected data to estimate flight parameters for six species: Flesh-footed Shearwater, Black Petrel, Westland Petrel, Southern Buller's Mollymawk, Southern Royal Albatross, and Gibson's Albatross. Albatross spent between 17–25% of flight time within the rotor sweep zone, Westland Petrel 11%, and Black Petrel and Flesh-footed Shearwater less than 5%. Albatross were generally more active during the day than petrels and shearwaters, although night flight activity was variable across species. This study provides the first speed data for Southern Royal Albatross and Gibson's Albatross, with all six species flying at similar median speeds, around 35 m/s. Flight height data were too noisy for precise collision risk modelling but offer a coarse indication of relative risk, useful for vulnerability assessments. Our results indicate that albatross species are likely at greatest risk from OWFs, with Westland Petrel also at some risk. Better flight height data is needed urgently, prior to the construction of OWF in the Southern Hemisphere. We conclude that existing GPS data cannot provide all the required flight parameters, and altimeters or bespoke technologies are required to fill this knowledge gap.

1. INTRODUCTION

Driven by greenhouse gas reduction targets to reduce human-induced climate change, renewable energy production has grown worldwide, with offshore windfarm (OWF) capacity increasing by 21% over the last decade (PWC, 2024) and is expected to grow from 117GW capacity in 2023 to 320GW by 2030 (Global Wind Energy Council, 2024). OWF are an attractive alternative to onshore windfarms, with less social opposition and more consistent and powerful winds (especially in Aotearoa New Zealand (McKinlay et al., 2025)) (Global Wind Energy Council, 2024; PWC, 2024). While the northern hemisphere is currently at the forefront of OWF energy production (Watson et al., 2025), several OWFs have recently been proposed in Oceania, with the first expected in Aotearoa New Zealand (henceforth Aotearoa) by the early 2030s (PWC, 2024).

Despite renewable energy being a positive shift from fossil fuels, OWFs have known environmental impacts; affecting wildlife through disturbance, habitat loss and modification, and collisions (Drewitt & Langston, 2006; McKinlay et al., 2025; Watson et al., 2025). This duality is especially pronounced with respect to seabirds, one of the most endangered groups in the world. Seabirds are affected by climate change (Croxall et al., 2012; Dias et al., 2019), yet are also at high risk of being negatively impacted by OWFs (Garthe & Hüppop, 2004). Wind turbines are known to create avian collision risks, reducing bird survival (Drewitt & Langston, 2006; Everaert & Stienen, 2007; Newton & Little, 2009), and have the potential to displace birds and impact their productivity (Dierschke et al., 2016; Hooper et al., 2017; Watson et al., 2025). While difficult to assess accurately – as it is challenging to collect all carcasses, particularly over the sea and of smaller species (Drewitt & Langston, 2006; Langston & Pullan, 2003; Stewart et al., 2007) – mortalities due to collisions with turbines have the potential to severely impact bird populations (e.g. Duriez et al., 2023; Everaert & Stienen, 2007; Lane et al., 2020), particularly those with slower life-histories, such as seabirds (Cook & Robinson, 2017; Schreiber & Burger, 2002).

Two common approaches to assess OWF impacts are vulnerability assessments and collision risk models. Vulnerability assessments use high-level data – such as conservation status, life history traits, and flight characteristics – to assign a risk score (Furness et al., 2013; Garthe & Hüppop, 2004; Reid et al., 2023) while collision risk modelling is a more statistically-focused approach, using a suite of parameters – such as shape and size of the bird, turbine dimensions, and bird flight characteristics – to model collision risk (Masden & Cook, 2016). Three important metrics (apart from species' habitat preferences) used in both of these assessments are: flight height, speed, and diurnal/nocturnal activity (Furness et al., 2013; Garthe & Hüppop, 2004; Masden & Cook, 2016). Flight height is considered one of the most important factors for assessing OWF risk (Cook et al., 2012; Furness et al., 2013; Masden & Cook, 2016): the amount of time spent within the rotor sweep zone is directly related to how likely the bird is to be struck by the turbine. Unfortunately, data on flight height are scarce (Thaxter et al., 2015), particularly for Procellariforms (Miller et al., 2025). Speed is another important parameter, influencing the duration within the rotor sweep zone and the likelihood of being struck, as well as the ability to avoid the turbines (Masden et al., 2021; Reid et al., 2023). Diurnal/nocturnal activity is largely useful to account for additional collisions during the night, outside of survey times (Furness et al., 2018), and can indicate nocturnal collision risk when turbines would be less visible to birds, or vice versa, may be attractive due to illumination.

Prior to the construction of OWFs, understanding how local seabirds may be affected is crucial. The impacts of OWFs are heavily dependent on species and location and must be assessed on a local scale (Duriez et al., 2023; Everaert & Stienen, 2007; Langston & Pullan, 2003). However, few of the required data are available for the seabird species in the Southern Hemisphere (Miller et al., 2025). Most insights into the OWF environmental impacts on seabirds originates from the Northern Hemisphere, but this information is not directly transferable to Aotearoa, or the Southern Hemisphere in general (McKinlay et al., 2025; Miller et al., 2025). The seabird assemblages, ecologies, and life histories in the two hemispheres differ, with the Southern Hemisphere having a greater diversity and abundance of Procellariforms, which are underrepresented in European assessments (Deakin et al., 2022; Miller et al., 2025). Aotearoa, in particular, is a seabird hotspot, with the number of endemic species, many which are Procellariiformes, surpassing that of all the countries combined (McKinlay et al., 2025; Taylor et al., 2000). Many of these species are threatened (Robertson et al., 2021) and have very little relevant flight information (Miller et al., 2025).

With the approach of OWFs in Australasia, the knowledge gap of Southern Hemisphere seabird flight parameters needs to be filled quickly. One potential source of relevant flight parameters is the plethora of GPS tracks that have already been deployed and retrieved for other purposes (e.g. distributions, movement ecology, fisheries interactions, *etc.*) (Carneiro et al., 2024). Depending on the GPS unit used, many of these will provide several needed flight parameters, such as speed, altitude, and diurnal/nocturnal activity. Sometimes individuals will be double-tagged with an activity recorder (time-depth recorder (TDR) or a global location sensor (GLS)), to aid in behavioural classification (e.g. Düssler et al., 2025), which provide data streams that could be exploited for better insights into the required flight parameters.

Here, we investigate if conventionally collected GPS tracking data, paired with secondary activity recorders (n = 84), during 2023-2025, could provide the necessary insights into the flight parameters for three albatrosses and three petrel species, all of which are at potential risk from OWFs. We use raw GPS flight height data and include a bootstrapping methodology to handle error, quantify instantaneous flight speed, and calculate nocturnal flight activity, with resting and flying determined by activity indicators. This work therefore will shed light into whether the large body of existing tracking data can be exploited to provide insights into OWF risks or if more targeted tracking efforts with specialised technologies will be required.

2. METHODS

All analyses were completed in R version 4.5.0 (R Core Team, 2025).

2. 1. Study Species

The six taxa included in this study were Flesh-footed shearwater | toanui (*Ardenna carneipes*), Black petrel | tākoketai (*Procellaria parkinsoni*), Westland petrel | tāiko (*P. westlandica*), Southern Buller's mollymawk | toroa (*Thalassarche bulleri bulleri*), Gibson's albatross | toroa (*Diomedea antipodensis gibsoni*), and Southern royal albatross | toroa (*D. epomophora*) (Table 1). All taxa except the Flesh-footed Shearwater are endemic to Aotearoa (Heather & Robertson, 2005), and all six are considered at risk or threatened (International Union for Conservation of Nature, 2025; Robertson et al., 2021), most notably by fisheries bycatch (Edwards et al., 2023). They are all characterised by limited or no relevant flight parameter data (Miller et al., 2025), and are likely to be negatively impacted by OWF developments (McKinlay et al., 2025; Reid et al., 2023).

Data from a total of 84 adults, tracked during the 2023/24 and 2024/25 breeding periods, were included in this study. Bar Gibson's and Southern Royal Albatrosses, each bird was deployed with GPS tags and secondary devices for other studies (e.g. Düssler et al., 2025; Waipoua et al., 2026), therefore their use in this study is opportunistic. Consequently, the GPS and activity recorder models and their deployment length and settings (such as fix rate) vary widely, reflecting the current mass of available tracking data.

All GPS units were attached to the back-feathers of the bird using water-proof tape, while TDRs and GLSs were attached to the tarsi of birds using customised housings (TDRs) or cable ties and metal/Darvic bands (GLSs). All device weights combined were <3% of body weights of the species they were attached to. For full details on tagging methodologies, see the original reports (Düssler et al., 2025; Mischler et al., 2025; Sagar et al., 2024; Waipoua et al., 2026). Trips were classified as the period between leaving and returning to the colony, with a 50 m buffer, which were longer than one day.

2.2. Behavioural Classification

To ensure that the flight parameters obtained from GPS tracking data reflect flight, and are not biased by birds resting on water, we mostly used data from secondary activity recorders to separate between behaviours. One of the functions of the activity recorders (GLS/TDR) is to record when the unit is wet or dry. Each GPS fix was time-matched with wet/dry status of the activity recorder which was then used to determine resting and foraging from flying. 'Wet' records were considered resting/foraging, and 'dry' as flying. Where activity indicators weren't co-deployed (n = 18), the speed distribution was visually assessed for bimodality, with the valley in the speed distribution used as a threshold for resting/foraging and flying behaviours (Jakubas et al., 2016; Shamoun-Baranes et al., 2011; Weimerskirch et al., 2006). Using this method, 10 km/h (2.8 m/s) was determined as the appropriate threshold to differentiate between resting (and drifting in currents) and flight. Where neither speed nor activity indicators are available, data were excluded (n = 3). Finally, all GPS locations over, or within 50 m of, land were removed from the dataset to remove further biases.

Table 1. Metadata for the datasets used in this study. Activity recorders were used to determine behaviour. Dates reflect the trips to deploy the units. Deployment length is how long the unit was on the bird but does not necessarily reflect trip lengths (see Table 2). Stage is breeding stage and reflects the data available in the metadata, hence the range of detail.

Taxa	Deployment site	No. birds	GPS Model	Dates	Tracking duration (weeks)	Phenological stage	Fix Rate (min)	Activity Recorder	STDB ID
Flesh-footed shearwater	Ohinau Island	31	TechnoSmart AxyTrek (10), Pathtrack nanofix (14), Catlog GenII (7)	February, 2025	0.9 (SD=0.4)	Breeding – chick rearing	5	TDR	2421
Black Petrel	Aotea | Great Barrier Island	6	PathTrak nanofix GEO	December 2023 – February 2024	9.3 |(SD= 0.8)	Breeding – incubating, chick rearing	15	TDR	2453
Westland Petrel	Punakaiki	17	Mobile Action i-gotU GT-120B	May - July, 2025	3.7 (SD= 1.7)	Breeding/pre-breed	60 (4), 30 (2), 10 (7), 10 second speed conditional (4)	GLS	2506
Southern Buller's Mollymawk	Snares Island | Tini Heke	14	Mobile Action i-gotU GT-120B	December 2024 – January 2025	0.6 (SD= 0.2)	Breeding – chick rearing (12), egg (2)	2 (14)	GLS	2458
Gibson's Albatross	Adams Island	5	Mobile Action i-gotU GT-120B	January – February, 2025	4.1 (SD=0.5)	Breeding – Egg (incubating)	5 (1), 15 (2), 20 (2)	GLS	2456
Southern Royal Albatross	Motu Ihupuku | Campbell Island	11	Mobile Action i-gotU GT-120B	December 2024 – January 2025	4.3 (SD=1.1)	Breeding	5 (1), 15 (5), 20 (5)	GLS	2455

2.3. Flight height

Except for height data obtained from TechnoSmart AxyTrek and Catlog GenII, all flight height data obtained from the GPS tags were given relative to an ellipsoid (WGS84, or EPSG:4326). The ellipsoid is a basic mathematical model of the Earth's surface as an ellipsis (Péron et al., 2020; Poessel et al., 2018). In order for the flight height data to be used in collision risk modelling and risk assessments, they must relative to mean sea level (Masden & Cook, 2016; Péron et al., 2020). This is achieved by subtracting the ellipsoidal height from the geoid height, where the geoid is a gravitation model of the Earth, approximating mean sea level. Thus, `height above mean sea level = ellipsoid height – geoid height`. Choice of geoid model can affect the outputs, and is a known source of uncertainty in estimating flight heights (Péron et al., 2020). Here we use the global XGM2019e geoid model, due to its better handling over the ocean than the commonly used EGM2008 (Pavlis et al., 2008; Zingerle et al., 2020). While a locally optimized geoid may be technically better, it will be more difficult to compare across datasets, as not all the birds fly within the scope of local geoids. For the TechnoSmart AxyTrek and Catlog GenII GPS tags, the raw altitude data was used, as the GPS has an internal geoid model.

To provide an indication of potential risk of the different study species, we place the flight height estimates in context with the rotor sweep zone. However, the exact rotor sweep zone for Aotearoa OWF instalments is still to be determined, as the proposed turbine designs are not yet confirmed. Here, we use a rotor sweep zone of 30 - 350 m, which is the current and proposed rotor sweep zone in Australia (Reid et al., 2023) and calculate the proportion of each taxa's flight height distribution that falls within this height band.

GPS-obtained altitude data are known to be error-prone (Thaxter et al., 2015), and several different ways have been used to account for the error, for example through state-space models (Péron et al., 2017; Ross-Smith et al., 2016). State space models can be challenging and computationally intensive to fit, and have a number of data-quality requirements, most notably a low error relative to movement stochasticity (Auger-Méthé et al., 2016), and a GPS fix rate near to the underlying movement process (Péron et al., 2020). For seabirds undertaking dynamic soaring, the underlying process is between 15 - 30 seconds (Sachs et al., 2013). Unfortunately, preliminary data exploration highlighted that these tracking data do not appear to meet the state space model requirements. Instead, here we remove the 1st and 99th percentiles of each taxa's flight height, as those values were considered biologically unrealistic (e.g. > 600 m).

To account for some of the error, we also present estimated time within the rotor sweep zone using Felis' (2019) bootstrapping method. The error is considered the difference between zero and the recorded altitude when the bird is determined to be at rest (i.e. activity recorder is 'wet'). 1,000 samples are taken from when the bird is resting and then added to a random 1,000 samples of altitude recordings when the bird is in flight.

2.5. Flight Activity / Night Flight Index

Following Miller et al., (2025), night flight index was calculated as per Dias et al., (2012): "*difference between the proportions of time spent in flight during darkness and during daylight, divided by the highest of these two values*". In flight was determined from the activity indicator (TDR/GLS) at the time of the GPS fix: wet is resting/foraging, and dry is flying. Where this was not available, speed was used (see section 2.2). Negative night flight index numbers indicate daytime activity, and positive indicate daytime. Local sunrise and sunset, obtained through the *suncalc* package (Thieurmel & Elmarhraoui, 2022), was used to determine night and day.

2.6. Flight Speed

Most, but not all, GPS models recorded instantaneous flight speed. Instantaneous flight speed, as groundspeed (i.e. relative to the ground, not the surrounding air) was provided by all tags deployed on Westland Petrel, Southern Buller's Mollymawk, and Gibson's and Southern Royal Albatrosses, and some Flesh-footed Shearwaters. All speeds were recorded as kilometres per hour, then converted into meters per second. Instantaneous flight speed was not recorded by GPS models deployed on Black Petrels and some Flesh-footed Shearwaters (both Pathtrak models). For these GPS models, speed could be derived from distance and time between GPS points, but at medium fix rates, this method tends to underestimate flight speed (Miller et al., 2025; Noonan et al., 2019), and hence flight speed for these individuals was not calculated.

3. RESULTS

Most Black Petrels flew west over the Tasman Sea, near Lord Howe Rise, traveling as far as ~2,500 kilometres from their colony on Aotea Great Barrier Island while all Flesh-footed Shearwaters flew east towards the Louiseville Ridge and near the Chatham Rise, up to 2,000 kilometres (straight line distance) from their Ohinau Island colony (Figure 1, Table 2). Westland Petrels stayed closer to coast, predominately around the West Coast and upper Te Waipounamu South Island, particularly Te Moana-o-Raukawa Cook Strait, and just south of Taranaki. They tended to stay near to shore, only travelling 1,100 km from their colony. Gibson's Albatross mainly flew west, but one individual flew north over the Tasman Sea, overlapping with the ranges of the Black Petrel, with a maximum distance of 2,700 km straight line distance from their colony. Meanwhile, staying mostly in shallower waters, Southern Royal Albatross were primarily distributed over the Campbell Plateau, around Rakiura, and up the east coast of Aotearoa, towards Kaikōura and the Chatham Rise. The maximum distance from their colony was 1,300 km. Southern Buller's Mollymawks were primarily distributed around southern Aotearoa and Rakiura, with some individuals travelling towards Tasmania, with the farthest flying 1,800 km from their colony.

Table 2. Flight tracks data. Maximum distance is straight line distance from colony. All data rounded to two significant figures.

Species	Average number of trips per bird	Average trip duration (weeks)	Maximum distance from colony (km)
Gibson's Albatross	1 (SD=0)	2.4 (SD=0.7)	2,700
Southern Royal Albatross	1.2 (SD=0.6)	2.5 (SD=1.31)	1,300
Southern Buller's Mollymawk	1 (SD=0)	0.3 (SD=0.2)	1,800
Flesh-footed Shearwater	1.3 (SD=0.5)	0.5 (SD=0.4)	2,400
Black Petrel	4.7 (SD=3.4)	1.4 (SD=1.2)	2,500
Westland Petrel	2 (SD = 1.1)	0.66 (SD = 0.9)	1,100

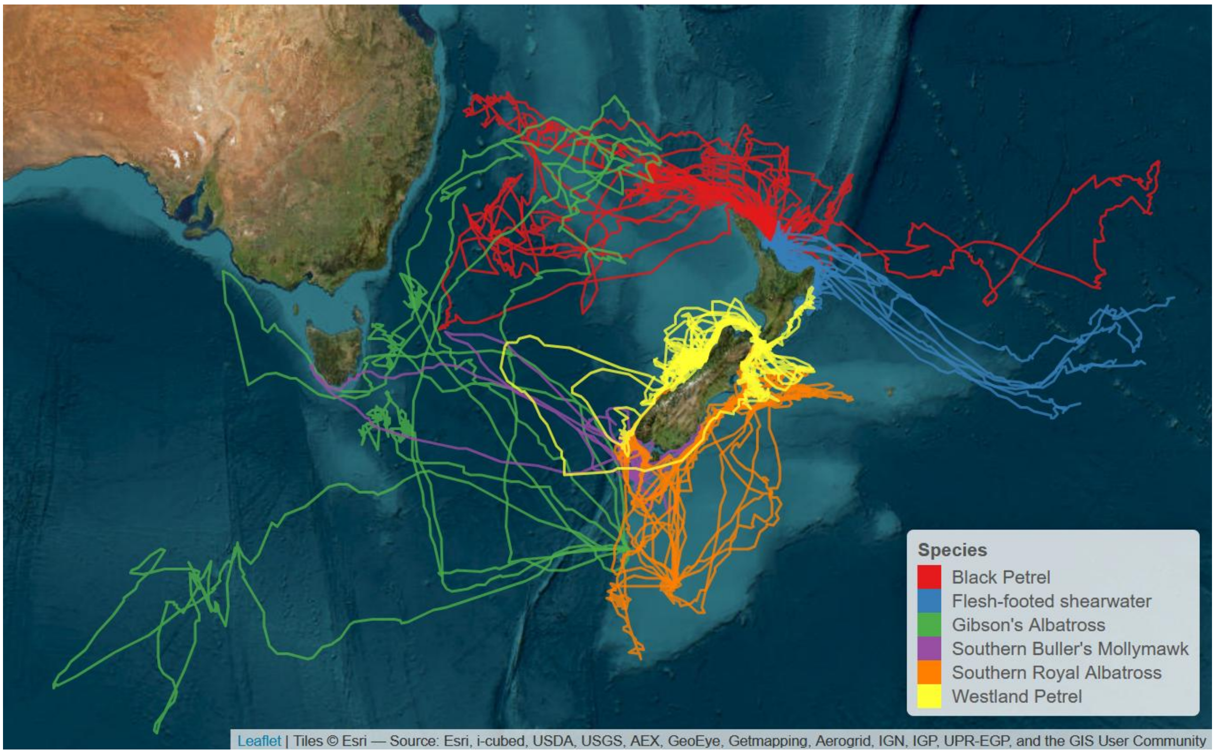

Figure 1. Flight paths of all individuals, each colour is a different species.

3.1. Flight Height

The three albatross taxa had the highest median flight height (7.7 m and 9.5 m for Gibson's Albatross and Southern Buller's Mollymawk, respectively). Of the albatross taxa, the Southern Royal Albatross had the lowest median flight height (2.4 m) (Table 2) while overall, the Westland Petrel flew the lowest on average, with all three Procellariidae having negative median flight heights. The interquartile range (IQR) was large for all species, between 45.7 m (Gibson's Albatross) and 16.4 m (Westland Petrel).

All birds spend some amount of time within rotor sweep zone (Table 2, Figure 2). The two smallest taxa - Flesh-footed Shearwater and Black Petrel - spend the least amount of time in the rotor sweep zone (4.5% and 2.5%, respectively), while the four larger birds spend more than 10% of the time within the rotor sweep zone; almost 25% each for Southern Buller's Mollymawk and Gibson's Albatross. The IQR for the percentage in rotor sweep zone is small for all species, between 1.9% (Southern Royal albatross) to 7.3% (Southern Buller's Mollymawk). Gibson's Albatross was the most variable, with an IQR of 12%. With the bootstrap error simulation method, the proportion in the rotor sweep zone increases to above 10% for all taxa. The mean difference between observed and bootstraps rotor sweep zone estimates was 7.7% (SD=4.9%). Westland Petrel and Southern Royal Albatross increased the most, by 14% and 11%, respectively, while Gibson's Albatross increased by 6.0% and the Southern Buller's Mollymawk dropped by 0.31%.

Table 3. Flight height data table. Ordered by median percent in rotor sweep zone. Error distribution is used for bootstrap and is when the birds are at rest. IQR = interquartile range. Rounded to 2 significant figures.

Species	Median flight height (m asl) [IQR]	Median % in rotor sweep zone [IQR]	Bootstrap median % in rotor sweep zone [IQR]	Median error for bootstrap [IQR]
Gibson's Albatross	7.7 [-16, 29]	25 [16, 28]	31 [29, 33]	7.8 [-23, 23]
Southern Buller's Mollymawk	9.5 [-6.4, 31]	23 [20, 28]	23 [20, 26]	8.4 [-5.7, 26]
Southern Royal Albatross	2.4 [-16, 21]	17 [15, 17]	28 [26, 30]	-1.5 [-21, 18]
Westland Petrel	-13 [-21, -4.3]	11 [9.4, 12]	24 [21, 27]	-15 [-31, 1.3]
Flesh-footed shearwater	0.24 [-7.9, 10]	4.5 [0.949, 12.4]	11 [9.1, 13]	0 [-10, 9.5]
Black Petrel	-0.47 [-9.6, 8.1]	2.5 [1.7, 3.1]	12 [11, 13]	-3.4 [-14, 7.1]

3.3. Flight Activity / Night Flight Index (NFI)

The three albatross taxa were more active during the day than at night, with Southern Buller's Mollymawk the most diurnal (NFI=-0.46), and Gibson's Albatross (NFI=-0.09) the least. The petrels were almost equally diurnal and nocturnal. The Flesh-footed Shearwater had the most variable NFI, with an IQR of 0.29, while the other taxa had an IQR between 0.11 and 0.16.

Table 4. Night flight index table. A value of 1 would indicate purely nocturnal and -1 purely diurnal. IQR = interquartile range. Rounded to 2 significant figures.

Species	Median [IQR]
Black Petrel	0.11 [0.07, 0.18]
Westland Petrel	0.09 [0.03, 0.14]
Flesh-footed shearwater	0.02 [-0.05, 0.24]
Gibson's Albatross	-0.09 [-0.16, -0.05]
Southern Royal Albatross	-0.23 [-0.28, -0.15]
Southern Buller's Mollymawk	-0.46 [-0.52, -0.36]

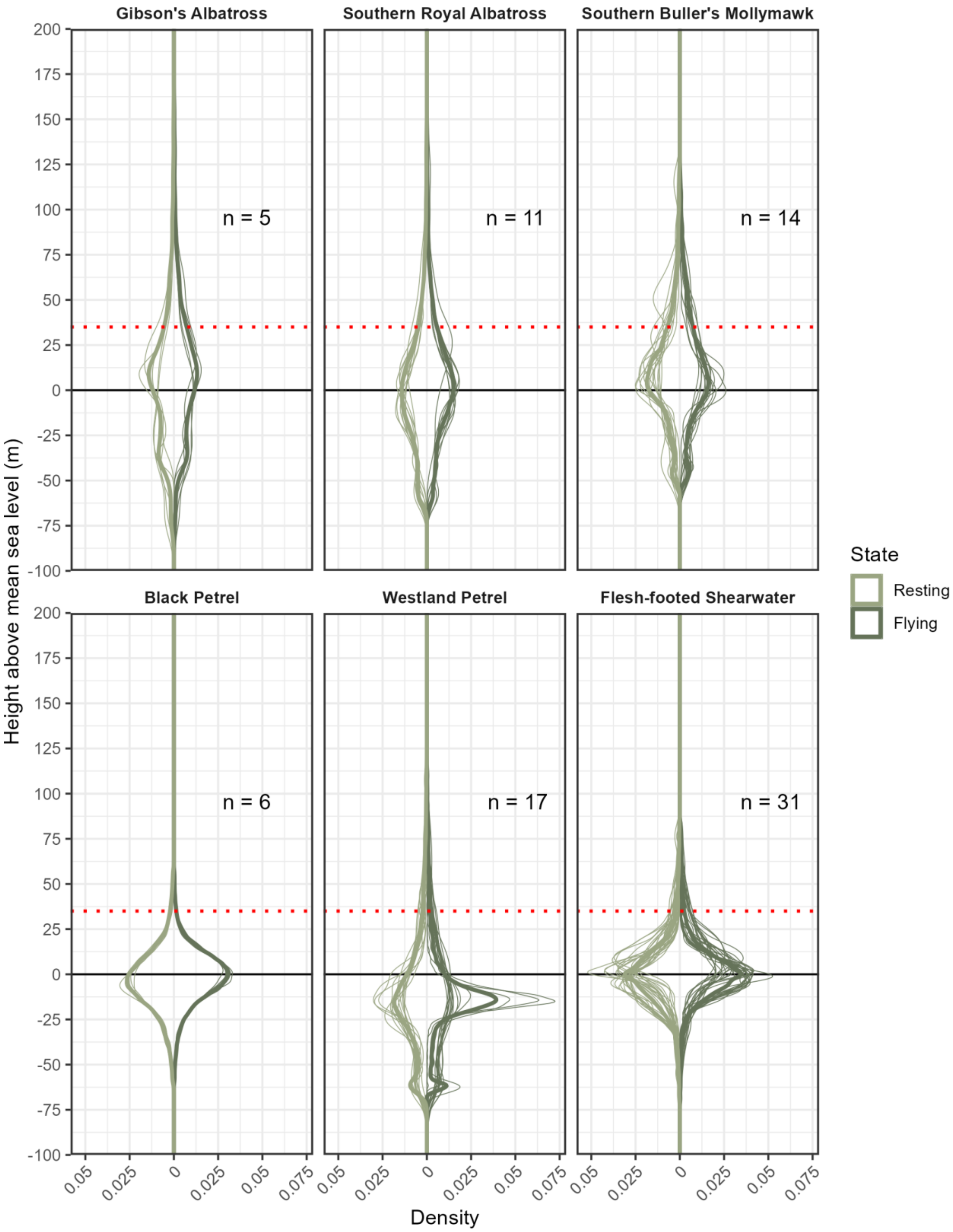

Figure 2. Flight height above mean sea level per taxa. Heights cut to -100 to 200 for improved visualisation. ‘Resting’ altitudes are light green lines and ‘flying’ altitudes are dark green lines. Thick lines are the overall density for each taxon while the thin lines represent each individual’s flight height. The dotted red line indicates the lower rotor sweep zone threshold (30 m).

3.4. Flight Speed

The median flight speeds of the five species were similar, but roughly in order of size, with the three albatross species having the highest average flight speeds, between 14 and 16 m/s, while the Westland Petrel and Flesh-footed Shearwater flew between 9.8 and 11 m/s (Table 4). Flesh-footed Shearwater had the highest maximum speed at 42 m/s, while the others had similar maximum speeds around 35 m/s.

Table 5. Table of instantaneous groundspeed obtained from GPS, rounded to 2 significant figures, and ordered by speed. IQR = interquartile range.

Species	**Median speed (m/s) [IQR]**	**Max speed (m/s)**
Gibson's Albatross	16 [12, 19]	36
Southern Royal Albatross	15 [12, 18]	34
Southern Buller's Mollymawk	14 [11, 17]	35
Westland Petrel	11 [8.9, 14]	36
Flesh-footed Shearwater	9.8 [7.7, 13]	42

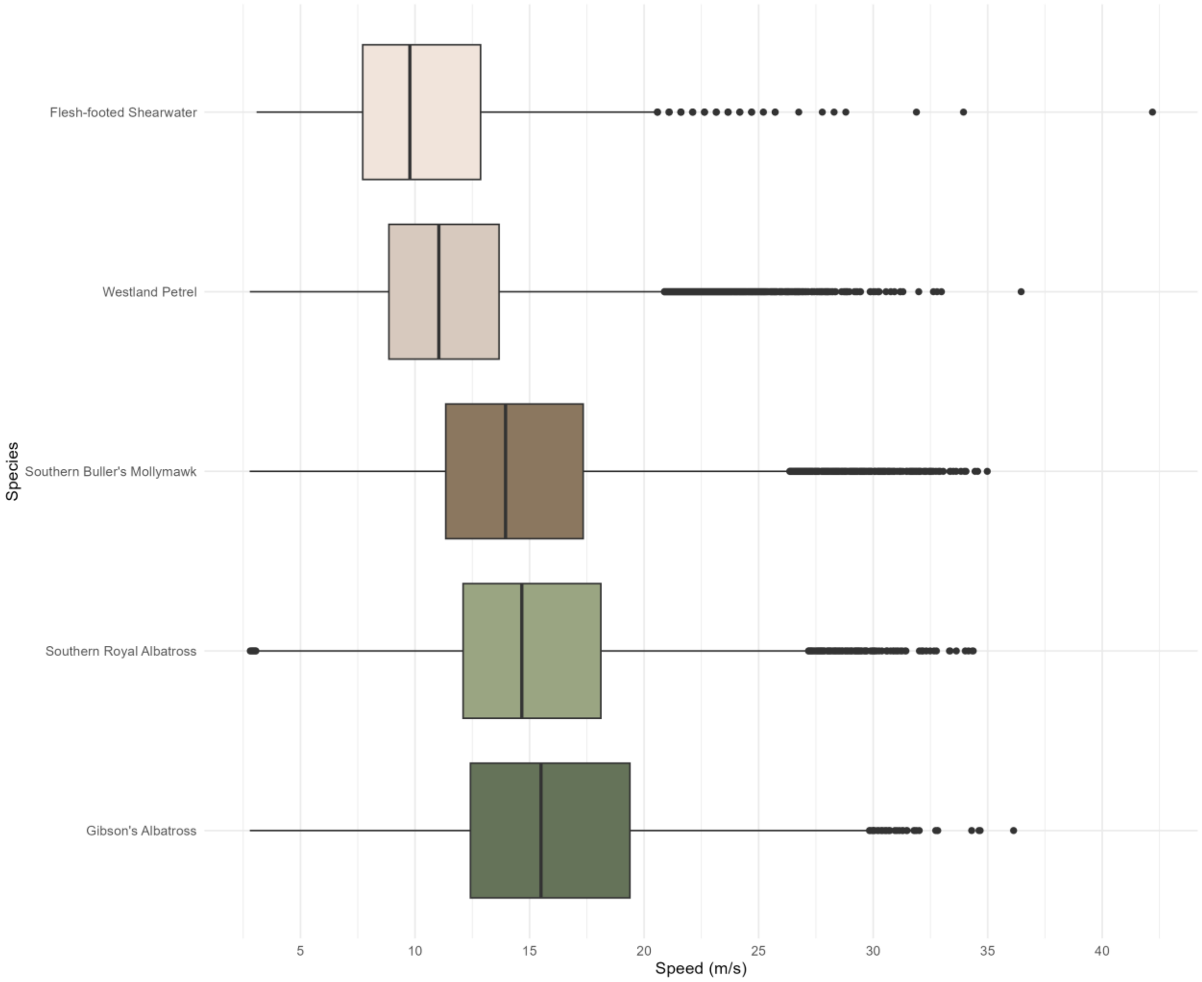

Figure 3. Instantaneous groundspeeds in meters per second (m/s) of the six species.

4. DISCUSSION

4.1. Summary of main findings

Here, we explored if existing GPS tracking data, paired with secondary activity recorders, can provide detailed insights into flight parameters required to assess OWF risk to Southern Hemisphere species. Our analyses provide the first detailed insights into relevant flight parameters for several of our study taxa: the first flight height estimates for all six taxa, and the first speed data for Southern Royal Albatross and Gibson's Albatross. In general, the flight parameters presented here provide a rough, broadscale overview of which Southern Hemisphere taxa may be at higher risk of OWFs collisions and could use further investigation. However, while unfortunately the data are too coarse to be used within collision risk models, they remain useful to inform higher-level risk assessments (e.g. Furness et al., 2013; Garthe & Hüppop, 2004; Reid et al., 2023).

We identified considerable potential for collision risks for all three albatross taxa investigated here. All three spend time within a rotor sweep zone of 30 – 350 m, particularly Southern Buller's Mollymawk and Gibson's Albatross, with roughly a quarter of their fixes within the rotor sweep zone. Once within the rotor sweep zone, the albatrosses are at high risk of colliding with the turbines, as they are large birds with low flight manoeuvrability due to high wing-loading and high flight speeds (Furness et al., 2013; Garthe & Hüppop, 2004; Reid et al., 2023). Furthermore, Southern Buller's Mollymawks breed on Hautere | Solander Island, just off Rakiura, and both Southern Buller's Mollymawk and Southern Royal Albatross frequented coastal waters around Rakiura and Southland, one of the proposed OWF areas in Aotearoa (McKinlay et al., 2025), further underscoring their potential risk. Albatross were also identified as the highest risk species in Australia by Reid et al., (2023)

These results are concerning as albatrosses are large species with slow life histories (Heather & Robertson, 2005; Schreiber & Burger, 2002) that are already under pressure (Dias et al., 2019), particularly from fisheries bycatch (Edwards et al., 2023). Adding in another mortality source has the potential to further destabilize these already precarious populations. More research into the flight height characteristics of these species is urgently needed before OWF are established in the Southern Hemisphere.

These results also highlight the importance of full height distributions, not just central tendency (Péron et al., 2020). All species have low median flight heights, yet four out of six still spend more than 10% of their time above 30 m (Figure 1). While this may be a feature of GPS error, many Procellariiformes do utilize a dynamic soaring flight style (Pennycuick, 1997; Thorne et al., 2023), resulting in variable flight heights, which could include relatively high peaks (Pennycuick, 1997; Richardson, 2011; Sachs et al., 2013). While the average flight height for Wandering albatross (*Diomedea exulans*) – congener to Gibson's and Southern Royal Albatross – is reported to be between 3-8 m, they had 'pull-ups' (the high, energy-gain portion of dynamic soaring) of up to 20 m (Pennycuick, 1997; Richardson, 2011). These pull-up heights are related to wind shear and wind speed (Sachs et al., 2013) and highlight that full flight distributions are required for good inferences.

While the albatrosses are predominantly diurnal, the smaller Procellariids were roughly equally diurnal and nocturnal. This puts them at more risk of collisions with the turbines; turbines will be less visible at night, and thus collision risk will likely be higher. Furthermore, the turbines may be illuminated (McKinlay et al., 2025), which will likely attract seabirds (Brown et al., 2023; Wilson, 2016). This is particularly true for the Westland Petrels which are shown here to be at some risk of flying within the rotor sweep zone and are very prone to attraction and disorientation by artificial lights at night (Wilson, 2016).

Accurate flight speed data are essential for collision risk models, altering the outputs considerably (Masden et al., 2021). This is the first flight speed data available for Gibson's and Southern Royal Albatrosses (Miller et al., 2025) and should be considered accurate as instantaneous speed from GPS is obtained through the Doppler effect (Safi et al., 2013). Higher flight speed is linked to lower collision risk as the birds spend less time within the rotor sweep zone (Masden et al., 2021; Masden & Cook, 2016). Conversely, when considered in the context of manoeuvrability, for larger birds, such as albatrosses, speed is also associated with greater collision risk as they are less able to take evasive action (Reid et al., 2023).

4.2. Comparison against previous studies

Albatross, both greater (*Diomedea*) and lesser (*Thalassarche*), are thought to have a mean flight of between ~3 – 13 m (Miller et al., 2025), which is broadly congruent with the central tendency for the flight heights for the albatross studied here. The median flight height of the Southern Royal Albatross appears to be slightly lower, however. It is likely that other similar albatross taxa, with similar flight styles, will have comparable flight profiles and collision risks to those presented here. It is difficult to fully compare the petrels and shearwater flight heights presented here with those reported previously as their median is below zero. However, the general trend of smaller seabirds flying lower than larger seabirds was also observed by Pennycuick (1997).

Expert opinion places all the species here within the rotor sweep zone 10% of the time (Miller et al., 2025; Reid et al., 2023). This is a cautionary approach that the result from the bootstrapping method supports for the Black Petrel and Flesh-footed Shearwater but would underestimate the risk for the albatrosses and Westland Petrel. However, in general, assuming at least 10% within the rotor sweep zone is a good minimum baseline for all the species before higher fidelity data are collected.

The speed data for Westland Petrels and for Buller's Mollymawk was almost twice as fast as that reported in (Miller et al., 2025). This is likely due to the data for these species being derived from distances between GPS fixes rather than instantaneous speed (Miller et al., 2025). The method used to obtain speed is variable and not always discussed. Here, speed was derived from GPS-provided instantaneous speed via the Doppler effect, which is generally of high quality (Safi et al., 2013). The speed for the Flesh-footed Shearwaters was in line with previous studies, and there was no previous speed data for the albatrosses. The overall theme of larger birds with greater wing loading flying faster is reflected in the literature (Spear & Ainley, 1997)

Night flight index values are largely congruent with those in the literature (Miller et al., 2025). Albatross are thought to be more diurnal than petrels and shearwaters, which is reflected here. However, Procellariiformes are very variable in their nocturnal flight activity (Miller et al., 2025), responding to different conditions such as lunar phase (Bonnet-Lebrun et al., 2021; Yamamoto et al., 2008); thus, longer deployment periods would be needed to gain a full picture of each taxon's nocturnal flight activity.

4.3. Limitations

GPS is known to be an imperfect tool for determining flight altitudes, with authors often citing error in the realm of 20 m (Ens et al., 2008; Lato et al., 2022; Thaxter et al., 2015). The error is dominated by noise, rather than bias (Schaub et al., 2023) – although see Lato et al., (2022) – and is inversely related to fix rate (Bouten et al., 2013; Thaxter et al., 2015). The error simulation method (Felis et al., 2019) is one way of handling the errors but makes several assumptions. Most notably, it ignores all GPS quality metrics (e.g. dilution of precision, number of satellites) and assumes GPS error is the same while stationary as when moving, despite GPS being known to be of better accuracy when moving (Lato et al., 2022). However, it is worth considering as an extra piece of information to inform risk assessments.

Our results underscore that different approaches are needed to obtain finer-detail flight height data. One option is higher resolution GPS, which are known to be more accurate (Bouten et al., 2013; Thaxter et al., 2018) and may allow the use of state space models. Another option is altimeters, which use barometric pressure to estimate flight height (Johnston et al., 2023; Lato et al., 2022; Thaxter et al., 2015). These are generally heavy units – although some lighter ones exist (Thaxter et al., 2015) – that can only be deployed on larger birds, especially if co-deployed with an activity recorder or GPS. Altimeters require regular pressure calibration, so dual deployments are useful (Garthe et al., 2014; Thaxter et al., 2015). Considering their large size and high risk of flying within the rotor sweep zone, albatrosses are a perfect candidate for future deployments of these units.

If future studies obtain data with less noise, it will also be possible to investigate how flight height differs by sex, behaviour, and phenology. Some seabird species are sexually dimorphic (Cleasby et al., 2015; Schreiber & Burger, 2002; Shaffer et al., 2001) or may be monomorphic but display different behaviours dependant on sex (Stienen et al., 2008). For example, sexually dimorphic albatrosses show differences in flight speed, with the larger males flying faster (Shaffer et al., 2001; Wakefield et al., 2009). Sex could also play a role in flight height differences between sexes could influence OWF collision risk, potentially leading to sex-biased impacts, with population-level consequences.

4.4. Conclusions

We have identified that albatrosses are likely at high risk of OWFs. While the data here are too coarse for formal collision risk modelling, they provide a high-level indication which species may be most impacted by OWFs. As a long-lived species with slow life histories, any extra albatross mortalities due to OWF collisions could impact already strained populations. Further investigation is urgently needed into the flight parameters of albatrosses prior to the construction of OWF. The current mass of existing GPS tracks therefore cannot provide these data. However, future deployments of more sophisticated altimeters or high-resolution GPS may enable the higher accuracy data required for formal collision risk modelling, and ultimately, avoidance of adverse effects from OWFs on these species.

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