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REVIEW

A global review of Procellariiform flight height, flight speed and nocturnal activity: Implications for offshore wind farm collision risk

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Abstract

1. Offshore wind farms are a key component of the transition to renewable energy generation and are planned globally. Procellariiformes (albatrosses, petrels, shearwaters and storm-petrels) include the most threatened and abundant seabird families, yet their risk of collision with offshore wind turbines remains virtually unquantified because we lack the ecological information necessary to parametrise Collision Risk Models (CRMs)
2. However, Procellariiformes are relatively well-studied in academic literature, presenting the opportunity for systematic review through a collision-risk lens. Here, we conduct meta-analyses to calculate species-level values for core CRM parameters: flight height, flight speed and nocturnal flight.
3. Our systematic review returned 163 studies, providing excellent species coverage (>1 parameter value for 119 of the 145 Procellariiform species). We compiled a flight parameter database with the most values for flight speed and nocturnal flight, while values for Procellariiform flight height were scarce and lacked empirical data.
4. Procellariiformes flew at speeds up to 28 $\mathrm{ms^{-1}}$ with species flight speeds generally prescribed by aerodynamic and flight morphology theory. Procellariiform flight activity varied across the diel cycle, with approximately a third of species flying more at night, a third flying more during the daytime and a third with no preference. Empirical studies characterised low (0–13 m) Procellariiform mean flight heights, but only for 21 species; expert opinion studies gave better coverage (104 species) but were highly uncertain when describing how frequently Procellariiformes may fly in a turbine's rotor swept zone.
5. We make recommendations for how to best parameterise CRMs and identify priorities for further research, such as the importance of 'instantaneous' GPS biologger flight speeds, reconsidering how we model nocturnality in CRMs (given the abundance of night-flying Procellariiformes), the merits of parameterising CRMs

with site-specific data over generic values and how new technologies can fill data gaps.

6. *Synthesis and applications*. We present a database of mean flight parameter values and uncertainty for Procellariiform species and flight groups. Flight speed and nocturnal flight parameter values are ready for use in CRMs; but flight height results are too uncertain for useful parameterization. To fill this key information gap, we recommend mandatory Procellariiform flight height data collection at planned offshore wind farms.

KEYWORDS
albatross, collision risk, meta-analysis, offshore wind farm, petrel, shearwater, storm-petrel

1 | INTRODUCTION

In 30 years, offshore wind energy has grown from single proof-of-concept turbines to gigawatt-scale windfarms, responsible for supplying 64.3 gigawatts of global electricity in 2023 (Global Wind Energy Council, 2023). Northern Europe (the industry's origin) and China currently share 96% of global offshore wind energy generation, but suitable areas for development are now being considered globally (Weiss et al., 2018). However, offshore wind farms have impacts on the environment, of which bird collision with turbines is an established risk (Perrow, 2019). Global offshore wind farm expansion will likely encounter local species with no proxies in northern Europe, where the bulk of offshore wind environmental impact knowledge resides, introducing novel and uncertain environmental impacts that can contribute to poorly informed decision-making (Searle et al., 2023). Procellariiform seabirds (albatross, petrels, shearwaters and storm-petrels) are a pertinent example, being especially prevalent in the Southern Ocean and understudied by the European offshore wind industry (Deakin et al., 2022). Given Procellariiformes include both the most numerically abundant seabird family (*Procellariidae*; Paleczny et al., 2015) and the most threatened seabird family (*Diomedeidae*; Dias et al., 2019), there is an urgent need to understand potential risks as offshore wind farm planning progresses at pace in regions with rich Procellariiform assemblages, such as South Africa, Brazil, Australia, New Zealand, Japan and the United States (4C-Offshore, 2024).

To inform the assessment of seabird collision risk posed by offshore wind farms, academic studies tend to focus on two areas. The first is metrics of species vulnerability to the effects of offshore wind farms, which can be used by policy makers and wind farm developers in early siting and planning phases (Garthe & Hüppop, 2004; Kelsey et al., 2018; Reid et al., 2023; Robinson Willmot et al., 2013; Wade et al., 2016). The second area of focus is informing impact assessment analyses and providing best-evidenced parameters to use in modelling, for example values for flight height, nocturnal activity, flight speed and macro-avoidance to use in collision risk models (CRMs; Cook et al., 2018; Furness et al., 2018; Johnston et al., 2014; Masden et al., 2021). Such academic studies on Procellariiformes outside northern Europe have only been published on the first focus area, providing vulnerability metrics for Procellariiformes in the US Atlantic shelf (Robinson Willmot et al., 2013), California (Kelsey et al., 2018) and Australia (Reid et al., 2023). This leaves a significant knowledge gap regarding what parameter values to use for Procellariiformes in CRMs, which requires an urgent response given the projected global expansion of offshore wind.

To parameterise Procellariiform collision risk models, data on key attributes of their flight are needed. Such data may already exist in the sizeable Procellariiform academic literature. To predict collisions, offshore CRMs use flight height to estimate the amount of time spent in a turbine's Rotor Swept Zone (RSZ), flight speed to estimate the rate of bird passage and the probability of being struck by rotating blades, and nocturnal flight activity to estimate how many additional collisions may occur during the unsurveyed night-time (Band, 2012; Masden & Cook, 2016; Smales et al., 2013). For each of these parameters, a higher value represents an increased risk of collision in the commonly used Band CRM (Band, 2012; Masden et al., 2021); however, higher speeds produce lower collisions in the Biosis CRM (Smales et al., 2013). CRMs also need parameters for seabird body length and wingspan, but appropriate databases for these already exist (e.g. Tobias et al., 2022), and a correction factor for within-windfarm turbine avoidance rate. Despite the sensitivity of CRMs to avoidance rate (Masden et al., 2021), it is the least well-known parameter because, unlike other parameters, avoidance can only be estimated after windfarms are built (Cook et al., 2018). Given that a recent review of Procellariiformes in Europe found avoidance information for only two species (Manx Shearwater *Puffinus* and Northern Fulmar *Fulmarus glacialis*; Deakin et al., 2022), despite ~30 years of offshore wind farm operation, and that offshore wind farms are yet to be built in the Southern Hemisphere (core Procellariiform range), we have not included avoidance rate in this review. Flight height and speed have been studied in Procellariiformes since early interest in their dynamic soaring flight (Alerstam et al., 1993; Pennycuick, 1982). The rapid rise of biologging, in particular high-frequency GPS trackers, has also seen studies capable of recording Procellariiform flight speed and height proliferate (Bernard et al., 2021). Studies on nocturnal flight activity have also been facilitated by biologging through

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the widespread use of geolocator loggers, which can characterise the amount of time spent flying day and night over many years (Dias et al., 2012). Combined with vessel survey studies in Procellariiform-rich waters, which can collect targeted data on flight heights, speeds and nocturnality (Ainley et al., 2015; Spear & Ainley, 1997b; Spear et al., 2007), published Procellariiform literature may contain a wealth of suitable information.

Here, we review Procellariiform academic literature and grey literature to identify best-evidenced values for key parameters in offshore collision risk models: flight height, flight speed and nocturnal activity. For each of the three parameters, our systematic review seeks to: (1) conduct meta-analyses to calculate parameter values and their uncertainty for individual species and species grouped by flight characteristics; and (2) summarise the state of knowledge, identify gaps, and prescribe advice on how to use results to inform collision risk modelling of Procellariiformes.

With this approach, our aim was to produce a robust and comprehensive parameter database to support Procellariiform collision risk modelling for offshore wind farm impact assessment for those species for which data exist and identify data gaps that warrant future study. Alternatives to such a database include: reliance on single studies as an industry standard, for example flight speeds from Alerstam et al. (2007) used in the UK for gulls (*Larus* spp. and *Rissa* sp.; JNCC et al., 2024), which risk being unrepresentative; or potentially ad hoc changes to the best-evidenced parameters as successive impact assessments expend greater cumulative effort searching the literature. As offshore wind farm planning progresses at pace in regions with rich Procellariiform assemblages, a collision risk model parameter database combined through meta-analyses of systematically reviewed literature, makes a timely contribution to reducing impact assessment uncertainty for albatross, petrels, shearwaters and storm-petrels, whilst supporting efforts to decarbonise the global economy and transition to renewable energy.

2 | MATERIALS AND METHODS

2.1 | Procellariiform flight database

We conducted our systematic review using Web of Science and Google Scholar to search for peer-reviewed and grey literature. We first conducted a broad search to identify offshore wind farm content related to Procellariiformes, with (procellariiform OR procellarid OR albatross OR petrel OR shearwater) AND "offshore wind*"; and then conducted species-specific searches with terms likely to catch parameter values of interest e.g. ("wedge-tailed shearwater" OR "Puffinus pacificus" OR "Ardenna pacifica") AND (height OR asl OR masl OR altitude OR speed OR nocturnal OR night OR collide*). Following the PRISMA workflow (Page et al., 2021), two reviewers (MM, SP) independently screened the first 300 records returned by the broad search and the first 100 records returned for each species-specific search; then retrieved and assessed full-text reports for screened-in records. Searches were carried out until January 2024. During screening, we excluded records if they did not relate to Procellariiformes (or the target of species-specific searches) or were terrestrially focussed (i.e. observations of flight over land). During full-text assessment, we excluded reports that did not provide quantitative values related to flight height, speed or nocturnality. The broad search returned 1919 records, of which 162 were screened in, 160 full-text reports were retrieved and assessed, and 11 reports used. Reviewing the reference lists of these 11 reports yielded a further four reports with quantitative values for inclusion. Species-specific searches ranged from 6020 (Wandering Albatross *Diomedea exulans*) to 10 (Rapa Shearwater *Puffinus myrtae*) records returned for each species (for species-specific search strings, record screening, and report assessment results, see the Procellariiform flight parameter database constructed from studies reviewed in this paper; Miller et al., 2025). For species searches and subsequent analyses and reporting, we followed the Birdlife International taxonomy classification for Procellariiformes (BirdLife International, 2022). No ethical approval was required, as no fieldwork was performed.

Values were extracted from reports as quoted in text or tables, digitised from figures (PlotDigitizer, 2024), or in some cases, calculated from quoted model coefficients. To avoid replication, when literature review reports were identified, we used their cited references to extract parameters from the original studies. If a literature review report calculated a new value from the original studies, or the original study source was unclear, we used the review-presented values. With the intention of creating a detailed and versatile reference database for future research, we extracted parameter values as reported in studies, and metadata on study method (summarised as: biologger, vessel-based, aerial/land-based or expert opinion/literature review), location (site and marine region; UN Geospatial Information Section, 1995) and species' phenological stage (summarised as: incubation, chick-rearing, migration, wintering or fledgling/juvenile/immature). When multiple parameter values were reported by the same study, for example flight speeds reported for males and females, we preserved these subsets in the database, accounting for non-independence in later meta-analyses.

Report assessment from both the broad and species-specific searches returned 169 reports with suitable information on Procellariiform flight height, speed and nocturnality parameters. However, the 169 studies provided values that differed in their description of the three parameters, and, to ensure our meta-analyses would not combine 'apples with oranges' (Harrer et al., 2022), we divided differing descriptions of each parameter into separate subparameter groups (Table 1). Six reports provided values incompatible with subparameter groupings (e.g. a maximum flight height value could not be included in the mean flight height subparameter) and were archived in the Procellariiform flight parameter database (Miller et al., 2025) as 'anecdotal' information. For height, subparameters of mean flight height and time in the RSZ were partitioned given inherently different interpretations. As offshore wind turbines have increased in size, the air gap (the minimum height of turbine blades above the sea) considered by studies has also increased. Given that greater turbine air gaps reduce the amount of time seabirds spend flying within the RSZ (Johnston et al., 2014), we summarised time in the RSZ for three air gaps considered in studies (10, 20 and 30 m; Figure S1 in Supporting Information). We note that turbine size continues to increase, with air gaps of 40 m planned (RWE Renewables UK, 2024). For speed, we partitioned subparameters of flight speed, maximum speed (which we consider useful for setting upper bounds), and whole trip speed (trip distance divided by trip duration, which could be a useful lower bound for flight speed, acknowledging that some portions of a trip may be spent resting on the sea surface). Speeds from geolocator studies were not included, given the impact of their 300–400 km positional error (Halpin et al., 2021) on trip distance calculation. All flight speed values were expressed relative to ground speed, the preferred input in CRMs (Masden, 2015). All nocturnal activity descriptions were converted to the Night Flight Index (NFI), the difference between the proportions of time spent in flight during darkness and during daylight, divided by the highest of these two values (Dias et al., 2012). NFI varies between −1 when all flight activity each day occurs in daylight, and 1 when all flight activity takes place in darkness.

2.2 | Meta-analysis

We aimed to use quantitative meta-analyses of study-reported values to calculate species means for each of the subparameters. However, quantitative meta-analysis requires at least an estimate of the effect size and its standard error (Higgins et al., 2023), the latter of which was not readily available for either of the two height subparameters. For time in the RSZ, we instead used a semi-quantitative approach to describe effect size certainty: first, ranking studies into High, Medium, or Low quality; and then translating these quality rankings into weights (1, 0.66 or 0.33, respectively) when combining studies with a weighted mean. Several studies already included species-specific, three-tier uncertainty classifications (e.g. Kelsey et al., 2018; Robinson Willmot et al., 2013), which we mapped onto our H,M,L quality classes. For the remaining studies, quality was classified as: Low, if based on limited anecdotal observations; Medium, if based on either extensive anecdotal observations or limited empirical data; or High, if based on extensive empirical data. For mean flight height, studies were too limited to sensibly average, and raw study values were presented instead. For speed and nocturnal activity subparameters, quantitative meta-analyses were performed. To standardise meta-analysis inputs, study values were converted to mean ± standard deviation (SD). Studies reporting standard error or 95% confidence intervals were converted to SD following Higgins et al. (2023), while study-reported median, minimum and maximum values were converted to mean ± SD using R package estmeansd (McGrath et al., 2023). Using the R package Meta (Balduzzi et al., 2019), species-specific meta-analysis models were constructed with study values for mean ± SD and sample size (number of birds). Meta-analysis models followed the inverse-variance approach (when calculating the pooled mean, studies with lower variance are given higher weight) and had a random effect structure to account for non-independence in studies that reported multiple values (e.g. flight speeds for males vs. females or in headwinds vs. tailwinds). We performed meta-analysis of means with a log transformation for speed subparameters and meta-analysis of proportions with a logit transformation for the NFI. We inspected models using the τ^2 statistic to measure variance in the distribution of true effect sizes and Higgins & Thompson's I^2 statistic to quantify between-study heterogeneity (Harrer et al., 2022). Where only a single study provided the subparameter value for a species, no meta-analysis could be performed and the average value and uncertainty we present are those reported in the original study.

2.3 | Procellariiform flight groups and reporting of results

To summarise subparameter values, we grouped species based on morphology and flight style and calculated group mean and standard deviation. We used the Procellariiform flight groups identified in Spear and Ainley (1997a), with the addition of novel flight groups for great albatrosses, sooty albatrosses, *Procellaria* petrels, *Calonectris* shearwaters and diving-petrels to cover all species. Flight group mean ± SD were created for all subparameters, apart from mean flight height, by pooling values from all species within each flight group and then following either quantitative meta-analysis or semi-quantitative weighted means as above. Quantitative meta-analysis results are presented as mean ± SD, as SD is an input requirement in stochastic collision risk models (e.g. https://dmpstats.shinyapps.io/sCRM/). Semi-quantitative meta-analysis results for time in the RSZ are presented with a weighted mean and the minimum and maximum values reported by studies. Mean flight height values are presented in their raw study format. A Procellariiform flight parameter database was constructed for this review, providing values extracted from studies, metadata, meta-analysis results and recommendations for CRM (Miller et al., 2025).

3 | RESULTS

3.1 | Systematic review summary

The systematic review found the greatest number of studies on Procellariiform speeds, followed by nocturnal flight activity, with height studies being the rarest (Tables 1 and 2). Excellent species coverage was attained with information on at least one flight parameter for 119 of 145 Procellariiform species (Table 3). Information on at least two flight parameters was found for 94 species, while information on all three parameters was found for a subset of 57 species. All flight groups were represented, with a median of five studies per flight group for flight speed and NFI subparameters,

TABLE 1 Subparameters of key Collision Risk Model (CRM) parameters identified from a systematic review of Procellariiform literature.

CRM parameter	Subparameter	Qualifier(s)	Extracted data format	Summary method	*n* studies
Height	Mean flight height (m)	Must be expressed above sea level. Must describe the central trend of flight height data	Varied (raw study values)	None (raw study values)	7
	Proportion of time in RSZ (%)	Must relate to turbine air gaps of 10, 20 or 30 m	Mean + H, M, L study quality classification	Weighted mean	10
Speed	Flight speed (ms^{-1})	Must represent or include transiting flight behaviour	Mean ± SD + *n* birds	Meta-analysis of means	61
	Maximum speed (ms^{-1})		Mean ± SD + *n* birds	Meta-analysis of means	26
	Whole trip speed (ms^{-1})		Mean ± SD + *n* birds	Meta-analysis of means	42
Nocturnal activity	Night Flight Index (NFI)	Must include % of time in flight during daylight and darkness.	Mean ± SD + *n* birds	Meta-analysis of proportions	64

Note: Species-specific subparameters were calculated by combining studies using quantitative meta-analysis or semi-quantitative meta-analysis following a High-, Medium-, Low-quality classification. Mean flight heights were not combined due to limited study availability. Cumulative total of *n* studies is >163 as individual studies often contained information for multiple subparameters.

four studies per flight group for time in the RSZ and two studies per flight group for trip speed, maximum speed and mean flight height (Table 2). The small albatrosses flight group had the most studies across different subparameters, exceeded only by Manx-type shearwaters for studies on time spent in the RSZ and great albatrosses for trip speed. In contrast, 15 flight group mean values were provided by single studies, best exemplified by prions with single studies on flight speed, trip speed and mean flight height (Table 2). Biologger studies were most frequent (145 studies), followed by vessel-based studies (9), aerial/land-based studies (5), and expert opinion/literature reviews (5). All trip and maximum speed studies relied on inputs from biologger studies. By contrast, 97% of nocturnal flight activity studies and 87% of flight speed studies relied on biologger studies; the former supplemented by literature reviews, and the latter by vessel and aerial/land-based studies (Table 2). Time spent within the RSZ was reliant mostly on expert opinion/literature reviews (40%) and vessel-based studies (30%), while a few studies of all data types represented mean flight height.

3.2 | Procellariiform flight results

Meta-analyses of reviewed studies estimated that giant-petrels had the fastest flight speeds of any Procellariiform group, followed by fulmars and sooty and great albatrosses (Figure 1a). Different shearwater groups spanned high and low speeds, while prions, *Procellaria* petrels, gadfly petrels, diving-petrels and storm-petrels had lower reported flight speeds. The Grey-headed Albatross *Thalassarche chrysostoma* had the highest average maximum flight speed of $28.5 \pm 6.4\,ms^{-1}$ (Figure 2a; Table 3). Procellariiform maximum speeds (17.8 ± 0.7 SE ms^{-1}) were significantly greater than flight speeds (9.3 ± 0.4 SE ms^{-1}), which were significantly greater than whole trip speeds (5 ± 0.6 SE ms^{-1}; LMM, $F_{(2,96.3)} = 107.18$, $p = < 0.0001$). Flight speeds differed by sampling platform (LMM, $F_{(2,15.4)} = 5.2$ $p = < 0.05$), with those from vessel survey studies (12.3 ± 1.2 SE ms^{-1}) being faster than GPS biologgers (8.8 ± 0.7 SE ms^{-1}; Tukey $p = < 0.05$) and ARGOS satellite biologgers (7.6 ± 0.9 SE ms^{-1}; Tukey $p = < 0.05$); speeds from the two biologgers did not differ (Tukey $p = 0.52$). This may have inflated the mean flight speeds of species only represented by vessel survey studies (Figure 2a and Figure S2; see Figures S3 and S4 for biologger only speeds).

Procellariiform nocturnal flight activity varied across the diel cycle, with approximately a third of flight groups and species flying more at night, another third flying evenly day and night, and a final third flying more during daytime (Figures 1b and 2b). Storm-petrels, fulmars and small gadfly petrels flew more at night; giant-petrels, large gadfly petrels and prions distributed their flight activity evenly between night and day; and shearwaters and albatrosses flew more during the day. Most flight groups showed relatively high variance in NFI (mean SD of 0.37; Table 2), particularly evident in Manx-type shearwaters and small albatrosses (Figure 1b). The White-winged Petrel *Pterodroma leucoptera* was the most nocturnal species, recorded performing 85% of flight at night, while the Campbell Albatross *Thalassarche impavida* was the most diurnal species, recorded performing 90% of flight during the day (Figure 2b; Table 3). NFI values from expert opinion/literature review were not significantly different from biologger studies (LMM, $F_{(1,4.9)} = 0.93$, $p = 0.38$).

Procellariiform mean flight height and percentage of time spent in the RSZ were highly uncertain due to limited data. The amount of time spent in the RSZ was highly variable for all flight groups, with the exception of storm-petrels. Studies reported contrasting observations, which masked the known relationship between greater turbine air gap and lower time in the RSZ (GLMM, $\chi^2_1 = 0.58$, $p = 0.44$; Figure 1c). Empirical studies were particularly scarce, with quantitative data on mean flight height available for 21 species (14% of Procellariiform species), each represented by one or two studies

TABLE 2 Literature coverage of Procellariiform flight parameters.

Procellariiform flight group (species richness)	Flight speed (ms^{-1}) Mean ± SD	*n* species, studies	Trip speed (ms^{-1}) Mean ± SD	*n* species, studies	Maximum speed (ms^{-1}) Mean ± SD	*n* species, studies	Night flight index Mean ± SD	*n* species, studies	Time in rotor swept zone (%) 10 m air gap mean (min–max)	20 m air gap mean (min–max)	30 m air gap mean (min–max)	n species, studies (all air gaps)	Mean flight height (m) Raw study value(s). Mean ± SD, range or median (*)	*n* species, studies
Great albatrosses (6)	10.2 ± 4.2	2	6.6 ± 5.8	4	21.2 ± 5.8	2	−0.53 ± 0.25	4			10	5	5 ± 2.1, 7.7 ± 5.5	2
Sooty albatrosses (2)	10.7 ± 2.7	1	8.4 ± 2.2	2			−0.44 ± 0.05	2			10	2		
Small albatrosses (14)	8.7 ± 6.4	10	5 ± 3	6	15.7 ± 16	7	−0.48 ± 0.61	10	24.2 (0–28)		8.8 (2.6–10)	12	0.04*, 3.5 ± 3.3, 4.4 ± 3.9, 5–10	4
Giant-petrels (2)	11.9 ± 4.5	2	6 ± 1.9	2			0.05 ± 0.18	2	24		10	2	3.2 ± 3.5, 5–10	2
Fulmars (5)	11 ± 2.3	5	7.7 ± 2.3	1	19.4 ± 3.4	1	0.38 ± 0.27	4	30 (0.8–47)	0.5 (0–1)	10	5	1.2 ± 2.3, 1–2	2
Procellaria petrels (5)	7.2 ± 4.9	3	6.1 ± 3.1	3	20.1 ± 3.1	1	0.02 ± 0.14	3	33		10	3		
Large gadfly petrels (21)	7.9 ± 6.1	8	4.9 ± 1	2	11.3 ± 1.9	1	0 ± 0.41	8	15.8 (0–32)		10	14		
Small gadfly petrels (20)	7.2 ± 3	9					0.25 ± 0.45	11	27 (0–32)	2.5	10	11		
Calonectris shearwaters (4)	8.2 ± 5.2	3	2.3 ± 0.3	1	21.7 ± 3.4	1	−0.39 ± 0.46	4		1.6 (1–2.5)	15 (10–25)	3	1.08 ± 0.97, 1.8 ± 2.7, 1–2	2
Surface-feeding shearwaters (5)	5.6 ± 6.9	5	3.9 ± 1.5	3	13.3 ± 6.9	2	−0.09 ± 0.49	5	21.6 (3.8–26)	0.2	8.4 (5.2–10)	5	0.84*, 1.22 ± 1.33, 0–5*	2
Diving shearwaters (2)	10.9 ± 5.6	2	3.5 ± 2	2	17.4 ± 1.3	2	−0.4 ± 0.53	2	32 (0–47)	3.8 (0–5)	18 (10–50)	2	1.21 ± 1.3, 0–5*	1
Manx-type shearwaters (19)	10 ± 5.4	9	2.4 ± 0.7	3	20.8 ± 3.4	1	−0.22 ± 0.81	6	1.8 (0–2)	0 (0–0)	10	9	1 ± 0.49, 0–5*	2
Prions (8)	8.7 ± 2.7	3	3.5 ± 0.7	1			−0.01 ± 0.2	5	19		10	8	1.3 ± 2.2	1
Diving-petrels (5)	7.1 ± 10.8	2					0.31 ± 0.5	3	2		10	5		
Oceanodroma (18)	5.5 ± 4.2	8	4.1 ± 1	1	9.8 ± 0.4	1	0.44 ± 0.27	7	0.9 (0.1–1)	0.6 (0–1)	0	12	1 ± 0.86, 0–5*	2
Frigate petrels (4)	9.3 ± 3.2	4	2.5 ± 1.5	1					2		0	3		
Oceanites (5)	7.8 ± 1.5	2					0.28 ± 0.27	1	1.3 (0.1–2)	0	0	3	1.07 ± 1.06, 1.3 ± 2.1	1

Note: For each flight group, subparameter mean values and uncertainties are shown in addition to the number of species these statistics represent, and the data type of supporting studies. Pie charts denote the number of studies, partitioned by data type: vessel-based (blue), biologger (red), land-based/aerial (green), expert opinion/literature review (purple). When flight group values come from a single species and single study, standard deviation (SD) reflects study-reported uncertainty.

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TABLE 3 Species and flight group collision risk subparameter values from systematic review and meta-analyses.

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	Flight speed *n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	Trip speed *n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	Maximum speed *n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	Night flight index *n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	*n* studies [stage] {region}
Northern Royal Albatross			3.5 ± 0.7	2 (21) [C, M, J] {WPa}	19.4 ± 14.7	2 (5) [I, M, J] {WPa}	−0.16 ± 0.09	1 (3) [M, J] {WPa}			10	M1 [U] {All}	5 ± 2.1	1 [J] {WPa}
Southern Royal Albatross			5.1 ± 2	2 (30) [I] {WPa, Ind}			0.07 ± 0.31	1 (10) [I] {Ind, WPa}			10	M1 [U] {All}		
Wandering Albatross	10.2 ± 4	13 (511) [I, C, J] {NPa, Ind, SAt}	6.8 ± 3.7	5 (66) [I, C] {WPa, SAt}	21.4 ± 1.7	4 (85) [I, C] {SAt, Ind}	−0.59 ± 0.18	7 (375) [I, C, M, W, J] {SAt, Ind, WPa}			10	M1 [U] {All}	7.7 ± 5.5	1 [I, C] {SAt}
Antipodean Albatross											10	M1 [U] {All}		
Amsterdam Albatross	10.5 ± 0.5	1 (199) [I, J] {Ind}	10 ± 14.6	2 (79) [I, C] {WPa, Ind}			−0.5 ± 0.21	2 (35) [I, J] {WPa, Ind}			10	M1 [U] {All}		
Great albatrosses	**10.2 ± 4.2**		**6.6 ± 5.8**		**21.2 ± 5.8**		**−0.53 ± 0.25**				**10**		**5 ± 2.1, 7.7 ± 5.5**	
Sooty Albatross			6.9 ± 1.1	1 (11) [M, W] {Ind}			−0.45 ± 0.05	2 (18) [C, M, W] {WPa, Ind}			10	M1 [U] {All}		
Light-mantled Albatross	10.7 ± 2.7	3 (17) [I, C] {Ant, SAt, Ind}	9.5 ± 2.3	1 (8) [C] {SAt}			−0.43 ± 0.05	3 (9) [I, C, M, W] {SAt}			10	M1 [U] {All}		
Sooty albatrosses	**10.7 ± 2.7**		**8.4 ± 2.2**				**−0.44 ± 0.05**				**10**			
Waved Albatross	8 ± 8.9	2 (25) [I, C] {EPa}					−0.68 ± 0.13	1 (5) [C] {EPa}	28			H1 [U] {EPa}		
Black-footed Albatross	9.7 ± 7	4 (203) [I, C] {NPa, EPa, WPa}	6.9 ± 1.4	2 (78) [I, C] {NPa}	15.6 ± 1.1	1 (42) [C] {NPa}	−0.08 ± 0.15	5 (112) [I, C, U] {WPa, NPa, All}	21.1 (0–28)			H1,L1 [U] {NPa, All}		
Laysan Albatross	10.2 ± 5.8	5 (167) [I, C] {NPa, EPa, WPa}	7 ± 1.5	2 (79) [I, C] {NPa}	15.5 ± 1.2	1 (42) [C] {NPa}	0.01 ± 0.42	5 (225) [I, C, U] {NPa, All}	23 (7.9–28)		2.6	H2,L1 [C, U] {NPa, All}	0.04*	1 [C] {EPa}
Short-tailed Albatross			2.9 ± 1.2	1 (28) [M, W] {NPa}			−0.28 ± 0.27	1 (L) [U] {All}	7.9			L1 [U] {All}		

Continues

TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	Flight speed *n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	Trip speed *n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	Maximum speed *n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	Night flight index *n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	Time in rotor swept zone (%) 20 m air gap (mean, min, max)	Time in rotor swept zone (%) 30 m air gap (mean, min, max)	Time in rotor swept zone (%) *n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	Mean flight height (m) *n* studies [stage] {region}
Atlantic Yellow-nosed Albatross	11.1 ± 1	1 (7) [U] {SAt}											5–10	1 [U] {SAt}
Indian Yellow-nosed Albatross							−0.62 ± 0.3	1 (9) [C] {Ind}			10	M1 [U] {All}		
Grey-headed Albatross	12 ± 1.9	4 (75) [I, C, U] {Ant, SAt}			28.5 ± 6.4	2 (21) [C] {SAt, WPa}	−0.76 ± 0.15	5 (63) [I, C, M, W] {SAt, WPa}			10	M1 [U] {All}	3.5 ± 3.3	1 [I, C] {SAt}
Black-browed Albatross	11.9 ± 1.5	5 (267) [I, C, U] {Ant, SAt}			6.1 ± 3.1	1 (16) [C] {EPa}	−0.53 ± 0.15	4 (89) [I, C, M, W] {SAt, WPa}	28		10	H1,M1 [U] {Ant, All}	4.4 ± 3.9, 5–10	2 [I, C, U] {SAt}
Campbell Albatross	9.9 ± 0.8	1 (86) [I, C] {WPa}			25 ± 3.4	1 (20) [C] {WPa}	−0.8 ± 0.05	1 (172) [I, C] {WPa}			10	M1 [U] {All}		
Buller's Albatross	5.7 ± 0.6	3 (86) [I, C] {WPa}	4.3 ± 1.4	2 (43) [I, C] {WPa}			−0.45 ± 0.04	2 (40) [I, C, M, W] {WPa}			10	M1 [U] {All}		
Shy Albatross	3.9 ± 2.8	1 (35) [F] {Ind, WPa}			7.7 ± 3.4	1 (44) [I, C] {Ind, WPa}	−0.52 ± 0.22	1 (9) [I, C] {Ind}			10	M1 [U] {All}		
White-capped Albatross			6.3 ± 4.8	1 (25) [C] {WPa}							10	M1 [U] {All}		
Chatham Albatross			4.8 ± 4.7	1 (3) [I, C, M, W] {WPa, EPa}	23.5 ± 3.4	1 (3) [I, C, M, W] {WPa, EPa}								
Salvin's Albatross	11.9 ± 1.8	1 (8) [U] {NPa, EPa, Ant}							28		10	H1,M1 [U] {EPa, All}		
Small albatrosses	**8.7 ± 6.4**		**5 ± 3**		**15.7 ± 16**		**−0.48 ± 0.61**		**24.2 (0–28)**		**8.8 (2.6–10)**		**0.04*, 3.5 ± 3.3, 4.4 ± 3.9, 5–10**	
Northern Giant-petrel	9.6 ± 6.2	2 (35) [I, C, F] {SAt, Ind}	6.5 ± 2.4	1 (17) [I] {SAt}			0.05 ± 0.18	1 (6) [I] {SAt}	24		10	H1, M1 [U] {Ant, All}	3.2 ± 3.5	1 [I, C] {SAt}

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1})		Trip speed (ms^{-1})		Maximum speed (ms^{-1})		Night flight index		Time in rotor swept zone (%)				Mean flight height (m)	
	Mean ± SD	*n* studies (*n* birds) [stage] {region}	Mean ± SD	*n* studies (*n* birds) [stage] {region}	Mean ± SD	*n* studies (*n* birds) [stage] {region}	Mean ± SD	*n* studies (n birds) [stage] {region}	10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Raw study value(s): Mean ± SD, median (*) or range	*n* studies [stage] {region}
Southern Giant-petrel	12.7 ± 2.2	4 (69) [I, C, F, U] {SAt, Ant, Ind}	5.8 ± 1.9	1 (26) [C] {EPa}			0.05 ± 0.18	1 (16) [I] {SAt}	24		10	H1,M1 [U] {Ant, All}	3.2 ± 3.5, 5–10	2 [I, C, U] {SAt}
Giant-petrels	**11.9 ± 4.5**		**6 ± 1.9**				**0.05 ± 0.18**		**24**		**10**		**3.2 ± 3.5, 5–10**	
Northern Fulmar	10.9 ± 2.3	4 (319) [I, C] {Nth, Arc, NPa}	7.7 ± 2.3	1 (4) [C] {NAt}	19.4 ± 3.4	1 (4) [C] {NAt}	0.57 ± 0.29	1 (M) [U] {All}	16.9 (0.8–33)	0.5 (0–1)		H4 [I, C, U] {NPa, NAt, All}		
Southern Fulmar	11 ± 2	3 (53) [C, U] {Ant}					0.17 ± 0.22	1 (27) [I, C] {Ant}	33		10	H1,M1 [U] {Ant, All}	1–2	1 [U] {SAt}
Antarctic Petrel	11.8 ± 1.7	2 (32) [C, U] {Ant}							47			H1 [U] {Ant}		
Cape Petrel	10.7 ± 1.2	3 (21) [C, U] {Ant, SAt}					0.28 ± 0.26	1 (6) [I, C] {Ant}	33		10	H1,M1 [U] {Ant, All}	1.2 ± 2.3	1 [I, C] {SAt}
Snow Petrel	12.3 ± 2.8	1 (52) [U] {Ant}					0.09 ± 0.13	1 (27) [I, C] {Ant}	33			H1 [U] {Ant}		
Fulmars	**11 ± 2.3**		**7.7 ± 2.3**		**19.4 ± 3.4**		**0.38 ± 0.27**		**30 (0.8–47)**	**0.5 (0–1)**	**10**		**1.2 ± 2.3, 1–2**	
Grey Petrel											10	M1 [U] {All}		
White-chinned Petrel	10.5 ± 2.6	3 (62) [I, C] {Ant, Ind, SAt}	8.5 ± 1.1	2 (43) [I, C] {Ind, SAt}	20.1 ± 3.1	2 (35) [I, C] {SAt}	0.01 ± 0.19	4 (174) [I, C, M, W] {WPa, SAt, Ind}	33		10	H1,M1 [U] {Ant, All}		
Spectacled Petrel			4.4 ± 1.6	2 (21) [M, W] {SAt}										
Westland Petrel	4.2 ± 0.5	2 (100) [I, C] {WPa}	5 ± 1.6	1 (32) [C] {WPa}			0.02 ± 0.1	2 (48) [C, M, W] {WPa}						
Black Petrel	8.6 ± 5.3	2 (20) [C, U] {EPa, WPa}					0.08 ± 0.15	1 (22) [C] {WPa}	33		10	H1,M1 [U] {EPa, All}		
***Procellaria* petrels**	**7.2 ± 4.9**		**6.1 ± 3.1**		**20.1 ± 3.1**		**0.02 ± 0.14**		**33**		**10**			
Tahiti Petrel	10 ± 5.2	1 (11) [U] {EPa}	4.4 ± 1.8	1 (21) [C] {WPa}	11.3 ± 1.9	1 (21) [C] {WPa}	0.12 ± 0.19	1 (21) [C] {WPa}	14		10	H1,M1 [U] {EPa, All}		

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1})		Trip speed (ms^{-1})		Maximum speed (ms^{-1})		Night flight index		Time in rotor swept zone (%)				Mean flight height (m)	
	Mean ± SD	*n* studies (*n* birds) [stage] {region}	Mean ± SD	*n* studies (*n* birds) [stage] {region}	Mean ± SD	*n* studies (*n* birds) [stage] {region}	Mean ± SD	*n* studies (n birds) [stage] {region}	10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Raw study value(s): Mean ± SD, median (*) or range	*n* studies [stage] {region}
Kerguelen Petrel									32		10	H1,M1 [U] {EPa, All}		
Murphy's Petrel	10.5 ± 5.4	1 (4) [U] {EPa}					−0.02 ± 0.12	3 (105) [I, C, M, W] {EPa, All}	10.5 (0–14)			H1,L1 [U] {EPa, All}		
Providence Petrel											10	M1 [U] {All}		
Kermadec Petrel	7.3 ± 4.9	2 (18) [C, U] {WPa, EPa}							14		10	H1,M1 [U] {EPa, All}		
Trindade Petrel							0.31 ± 0.16	1 (12) [I, C, M, W] {SAt}						
Herald Petrel	5.3 ± 5.8	1 (30) [I] {EPa}							14		10	H1,M1 [U] {EPa, All}		
Barau's Petrel			5.5 ± 0.7	1 (9) [I, C] {Ind}			0.08 ± 0.1	1 (88) [I, C, M, W] {Ind}						
Mottled Petrel	10.1 ± 0.4	2 (39) [M, U] {WPa, EPa}					−0.44 ± 0.22	1 (L) [I, C, M, W] {All}	24.1 (0–32)		10	H1,M1,L1 [U] {EPa, All}		
Hawaiian Petrel							−0.44 ± 0.22	1 (L) [U] {All}	11.5 (3.8–14)			H1,L1 [U] {EPa, All}		
Galapagos Petrel									14			H1 [U] {EPa}		
White-necked Petrel	7.3 ± 4.8	2 (58) [C, U] {WPa, EPa}							14		10	H1,M1 [U] {EPa, All}		
Juan Fernandez Petrel	9.9 ± 5.2	1 (63) [U] {EPa}							14			H1 [U] {EPa}		
Atlantic Petrel							0.01 ± 0.17	1 (40) [I, C, M, W] {SAt}						
White-headed Petrel							−0.34 ± 0.29	1 (3) [M, W] {Ind}	14		10	H1,M1 [U] {EPa, All}		
Great-winged Petrel									14		10	H1,M1 [U] {Ant, All}		

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	*n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	*n* studies [stage] {region}
Grey-faced Petrel	10.6 ± 1.9	1 (13) [I, C] {WPa}									10	M1 [U] {All}		
Large gadfly petrels	**7.9 ± 6.1**		**4.9 ± 1**		**11.2 ± 1.9**		**0 ± 0.41**		**15.8 (0–32)**		**10**			
Bulwer's Petrel	8.6 ± 1.9	2 (27) [I, U] {EPa, NAt}					0.5 ± 0.27	3 (93) [I, C, M, W] {NAt}	32		10	H1,M1 [U] {EPa, All}		
White-winged Petrel	9.3 ± 2.2	1 (10) [U] {EPa}					0.7 ± 0.04	1 (29) [M, W] {WPa}	32		10	H1,M1 [U] {EPa, All}		
Masatierra Petrel	9.3 ± 2.2	1 (9) [U] {EPa}							32			H1 [U] {EPa}		
Stejneger's Petrel	9.3 ± 2.2	1 (3) [U] {EPa}							32			H1 [U] {EPa}		
Cook's Petrel	9.3 ± 2.2	1 (17) [U] {EPa}					−0.14 ± 0.09	3 (35) [C, M, W, U] {WPa, All}	24.1 (0–32)			H1,L1 [U] {EPa, All}		
Pycroft's Petrel							0.66 ± 0.5	1 (12) [M, W] {WPa}	32			H1 [U] {EPa}		
Black-winged Petrel	7.8 ± 2.6	2 (118) [C, U] {WPa, EPa}					0.4 ± 0.3	1 (10) [M, W] {WPa}	32		10	H1,M1 [U] {EPa, All}		
Chatham Islands Petrel							0.11 ± 0.25	1 (48) [I, C, M, W] {WPa}						
Phoenix Petrel									14			H1 [U] {EPa}		
Soft-plumaged Petrel									14		10	H1,M1 [U] {Ant, All}		
Bermuda Petrel	6.5 ± 2	1 (10) [C] {NAt}					−0.08 ± 0.07	2 (10) [C, U] {NAt, All}		2.5		L1 [U] {All}		
Black-capped Petrel	6 ± 0.8	1 (6) [C, M, W] {Crb, NAt}					0 ± 0.21	1 (L) [U] {All}		2.5		L1 [U] {All}		

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	Flight speed *n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	Trip speed *n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	Maximum speed *n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	Night flight index *n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	Time in rotor swept zone (%) 20 m air gap (mean, min, max)	Time in rotor swept zone (%) 30 m air gap (mean, min, max)	Time in rotor swept zone (%) *n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	Mean flight height (m) *n* studies [stage] {region}
Cape Verde Petrel							0.32 ± 0.43	1 (13) [I, C, M, W] {NAt}						
Desertas Petrel	6 ± 4.1	1 (40) [I, C] {NAt}					0.34 ± 0.07	2 (84) [I, C, M, W] {NAt}						
Zino's Petrel							0.33 ± 0.42	1 (8) [I, C, M, W] {NAt}						
Small gadfly petrels	**7.2 ± 3**						**0.25 ± 0.45**		**27 (0–32)**	**2.5**	**10**			
Streaked Shearwater	9.8 ± 0.4	2 (28) [C] {NPa}					−0.56 ± 0.41	1 (38) [M, W] {NPa}			15 (10–25)	M1,L1 [M, W, U] {NPa, All}		
Sco poli's Shearwater	4.9 ± 6.4	2 (39) [C] {Med, NAt}	2.3 ± 0.3	1 (50) [C] {Med}	21.7 ± 3.4	1 (28) [C] {NAt}	−0.24 ± 0.21	2 (95) [C, M, W] {Med, NAt}		1		H1 [C] {Med}	1.8 ± 2.7	1 [C] {Med}
Cory's Shearwater	11.3 ± 4.5	2 (124) [M] {NAt, SAt, Med}					−0.34 ± 0.28	3 (282) [M, W, U] {Med, NAt, All}		2.5		M1 [U] {All}	1.08 ± 0.97, 1–2	2 [M, W, U] {NAt}
Cape Verde Shearwater							−0.53 ± 0.42	2 (51) [M, W] {Med, NAt}						
***Calonectris* shearwaters**	**8.2 ± 5.2**		**2.3 ± 0.3**		**21.7 ± 3.4**		**−0.39 ± 0.46**			**1.6 (1–2.5)**	**15 (10–25)**		**1.08 ± 0.97, 1.8 ± 2.7, 1–2**	
Wedge-tailed Shearwater	8.1 ± 3.6	2 (325) [C, U] {NPa, EPa}	4.1 ± 1.9	3 (144) [I, C] {WPa, Ind}	10.5 ± 1	2 (51) [C] {WPa}	−0.04 ± 0.59	4 (565) [C, M, W] {WPa, Ind, NPa}	26		7.1 (5.2–10)	H2,M1 [C, U] {NPa, EPa, All}	0.84*	1 [C] {EPa}
Buller's Shearwater	9.9 ± 3.6	1 (5) [U] {NPa, EPa}					0 ± 0.38	1 (L) [U] {All}	20.5 (3.8–26)		10	H1,M1,L1 [U] {EPa, All}		
Great Shearwater	10.2 ± 2.6	2 (33) [U] {NAt, SAt}	4 ± 0.9	1 (20) [I, C] {SAt}	21.8 ± 1.5	1 (20) [I, C] {SAt}	−0.05 ± 0.05	2 (58) [M, W, U] {SAt, All}	26	0.2		H2 [U] {SAt, All}	1.22 ± 1.33, 0*–5*	2 [All, M, W] {NAt, All}

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	*n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	*n* studies [stage] {region}
Flesh-footed Shearwater	9.9 ± 3.6	1 (2) [U] {NPa}	2.8 ± 1.6	1 (10) [I, C, M] {Ind}			−0.4 ± 0.11	2 (46) [M, W, U] {WPa, All}	3.8		10	M1,L1 [U] {All}		
Pink-footed Shearwater	4.5 ± 5.2	4 (118) [C, M, W, U] {EPa}					0 ± 0.38	1 (L) [U] {All}	20.5 (3.8–26)			H1,L1 [U] {EPa, All}		
Surface-feeding shearwaters	**5.6 ± 6.9**		**3.9 ± 1.5**		**13.3 ± 6.9**		**−0.09 ± 0.49**		**21.6 (3.8–26)**	**0.2**	**8.4 (5.2–10)**		**0.84*, 1.22 ± 1.33, 0*–5***	
Short-tailed Shearwater	10.7 ± 4.9	3 (12) [C, M, W, U] {WPa, NPa, Ant}	3.6 ± 3	2 (46) [C] {WPa, Ind}	17.1 ± 0.3	3 (42) [C] {WPa, Ind}	−0.5 ± 0.39	2 (78) [M, W, U] {WPa, All}	35.3 (0–47)		23.3 (10–50)	H1,M1,L2 [M, W, U] {NPa, All}		
Sooty Shearwater	12.2 ± 2.3	1 (110) [U] {NPa, EPa}	3.4 ± 1.4	1 (5) [I, C] {WPa}	22.5 ± 3.4	1 (1) [I, C] {WPa}	−0.34 ± 0.44	2 (119) [I, C, M, W] {SAt, All}	29.3 (2.5–47)	3.8 (0–5)	10	H2,M2,L1 [U] {NPa, All}	1.21 ± 1.3, 0*–5*	2 [M, W, U] {NAt, All}
Diving shearwaters	**10.9 ± 5.6**		**3.5 ± 2**		**17.4 ± 1.3**		**−0.4 ± 0.53**		**32 (0–47)**	**3.8 (0–5)**	**18 (10–50)**		**1.21 ± 1.3, 0*–5***	
Christmas Shearwater	14.1 ± 2.8	1 (2) [U] {EPa}							2			H1 [U] {EPa}		
Fluttering Shearwater							0.33 ± 0.55	1 (24) [I, C, M, W] {WPa}			10	M1 [U] {All}		
Hutton's Shearwater	6.4 ± 2	1 (26) [C] {WPa}	3 ± 3.3	1 (26) [C] {WPa}							10	M1 [U] {All}		
Black-vented Shearwater	14.1 ± 2.8	1 (2) [U] {EPa}					0 ± 0.38	1 (L) [U] {All}	1.5 (0–2)			H1,L1 [U] {EPa, All}		
Newell's Shearwater	14.1 ± 2.8	1 (24) [U] {EPa}							2			H1 [U] {EPa}		
Townsend's Shearwater	14.1 ± 2.8	1 (4) [U] {EPa}							2			H1 [U] {EPa}		
Manx Shearwater	8.6 ± 3.3	4 (197) [I, C] {NAt}	2 ± 0.3	1 (122) [I, C] {NAt}			−0.5 ± 0.39	2 (58) [M, W, U] {NAt, All}	1.5 (0–2)	0 (0–0)		H4,L2 [I, C, U] {SAt, NAt, All}	1 ± 0.49, 0*–5*	2 [M, W, U] {NAt, All}
Yelkouan Shearwater			2.8 ± 0	1 (7) [C] {Med}	20.8 ± 3.4	1 (7) [C] {Med}								

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	*n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	*n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	*n* studies [stage] {region}
Balearic Shearwater	11.2 ± 5.3	2 (136) [C, M] {Med}					−0.59 ± 0.03	1 (60) [I] {Med}					0*–5*	1 [U] {All}
Little Shearwater	14.4 ± 0.2	1 (3) [U] {NAt}					−0.48 ± 1.1	1 (4) [M, W] {NAt}			10	M1 [U] {All}		
Audubon's Shearwater	14.1 ± 2.8	1 (20) [U] {EPa}					−0.07 ± 0.28	2 (132) [I, C, M, W] {Crb, NAt, All}	2	0		H2 [U] {EPa, All}		
Manx-type shearwaters	**10 ± 5.4**		**2.4 ± 0.7**		**20.8 ± 3.4**		**−0.22 ± 0.81**		**1.8 (0–2)**	**0 (0–0)**	**10**		**1 ± 0.49, 0*–5***	
Blue Petrel	8.7 ± 3.6	1 (76) [U] {Ant}					0.01 ± 0.05	1 (12) [I] {SAt}	19		10	H1,M1 [U] {Ant, All}		
Broad-billed Prion							−0.01 ± 0.22	1 (63) [I, C, M, W] {SAt}	19			H1 [U] {Ant}		
Salvin's Prion									19		10	H1,M1 [U] {Ant, All}		
MacGillivray's Prion							−0.09 ± 0.22	1 (35) [I, C, M, W] {SAt}	19			H1 [U] {NPa, EPa, Ant s}		
Antarctic Prion	8.7 ± 3.6	1 (18) [U] {Ant}					−0.01 ± 0.06	1 (12) [I] {SAt}	19		10	H1,M1 [U] {Ant, All}	1.3 ± 2.2	1 [I, C] {SAt}
Slender-billed Prion	8.7 ± 3.6	1 (6) [U] {Ant}	3.5 ± 0.7	1 (69) [C] {SAt}					19		10	H1,M1 [U] {Ant, All}		
Fairy Prion							0.17 ± 0.02	1 (90) [I, C] {WPa}	19		10	H1,M1 [U] {Ant, All}		
Fulmar Prion									19			H1 [U] {Ant}		
Prions	**8.7 ± 3.6**		**3.5 ± 0.7**				**−0.01 ± 0.2**		**19**		**10**		**1.3 ± 2.2**	
Whenua Hou Diving-petrel							0.1 ± 0.59	1 (102) [M, W] {WPa}	2			H1 [U] {All}		
Peruvian Diving-petrel									2			H1 [U] {All}		
Magellanic Diving-petrel									2			H1 [U] {All}		

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TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	Flight speed *n* studies (*n* birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	Trip speed *n* studies (*n* birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	Maximum speed *n* studies (*n* birds) [stage] {region}	Night flight index Mean ± SD	Night flight index *n* studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	*n* studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	Mean flight height *n* studies [stage] {region}
South Georgia Diving-petrel	13.9 ± 3.1	1 (46) [I, C] {Ind}					0.29 ± 0.21	1 (8) [I] {SAt}	2			H1 [U] {All}		
Common Diving-petrel	7 ± 8.6	2 (49) [I, C] {WPa, Ind}					0.46 ± 0.33	2 (30) [I, C, M, W] {WPa, SAt}	2		10	H1,M1 [U] {Ant, All}		
Diving-petrels	**7.1 ± 10.8**						**0.31 ± 0.5**		**2**		**10**			
European Storm-petrel	4.2 ± 2.1	2 (81) [I, C] {Med}	4 ± 1	1 (6) [C] {NAt}	9.8 ± 0.4	2 (49) [I, C] {Med, NAt}	0.42 ± 0.13	1 (8) [M, W] {Med}		1		L1 [U] {All}	0*–5*	1 [U] {All}
Band-rumped Storm-petrel	7.5 ± 3.5	1 (4) [U] {EPa}					0.28 ± 0.27	1 (M) [U] {All}	1	0		H2 [U] {EPa, All}		
Matsudaira's Storm-petrel											0	M1 [U] {All}		
Black Storm-petrel	7.5 ± 3.5	1 (8) [U] {EPa}					0.28 ± 0.27	1 (L) [U] {All}	0.8 (0.1–1)			H1,L1 [U] {EPa, All}		
Ashy Storm-petrel	7.5 ± 3.5	1 (3) [U] {EPa}					0.28 ± 0.27	1 (L) [U] {All}	0.8 (0.1–1)			H1,L1 [U] {EPa, All}		
Least Storm-petrel							0.28 ± 0.27	1 (M) [U] {All}	0.8 (0.1–1)			H1,L1 [U] {EPa, All}		
Wedge-rumped Storm-petrel	7.5 ± 3.5	1 (30) [U] {EPa}							1			H1 [U] {EPa}		
Leach's Storm-petrel	6.5 ± 2.7	2 (120) [C,U] {NAt, NPa}					0.52 ± 0.21	2 (12) [M, W, U] {NAt, All}	1 (1–1)	1		H3,L1 [U] {NPa, All}	1 ± 0.86, 0*–5*	2 [M, W, U] {NAt, All}
Swinhoe's Storm-petrel											0	M1 [U] {All}		
Markham's Storm-petrel	7.5 ± 3.5	1 (14) [U] {EPa}							1			H1 [U] {EPa, All}		
Fork-tailed Storm-petrel							0.28 ± 0.27	1 (L) [U] {All}	0.8 (0.1–1)			H1,L1 [U] {NPa, All}		
Ringed Storm-petrel	7.5 ± 3.5	1 (16) [U] {EPa}							1			H1 [U] {EPa, All}		

Continues

TABLE 3 Continued

Species and flight group	Flight speed (ms^{-1}) Mean ± SD	Flight speed n studies (n birds) [stage] {region}	Trip speed (ms^{-1}) Mean ± SD	Trip speed n studies (n birds) [stage] {region}	Maximum speed (ms^{-1}) Mean ± SD	Maximum speed n studies (n birds) [stage] {region}	Night flight index Mean ± SD	Night flight index n studies (n birds) [stage] {region}	Time in rotor swept zone (%) 10 m air gap (mean, min max)	20 m air gap (mean, min, max)	30 m air gap (mean, min, max)	n studies and quality [stage] {region}	Mean flight height (m) Raw study value(s): Mean ± SD, median (*) or range	Mean flight height n studies [stage] {region}
Oceanodroma	**5.5 ± 4.2**		**4 ± 1**		**9.8 ± 0.4**		**0.44 ± 0.27**		**0.9 (0.1–1)**	**0.6 (0–1)**	**0**		**1 ± 0.86, 0*–5***	
White-faced Storm-petrel	9.3 ± 3.2	1 (2) [U] {EPa}	2.5 ± 1.5	1 (62) [I, C] {NAt}					2		0	H1,M1 [U] {EPa, All}		
White-bellied Storm-petrel	9.2 ± 3.2	1 (10) [U] {EPa}							2			H1 [U] {EPa}		
Black-bellied Storm-petrel	9.3 ± 3.2	1 (7) [U] {EPa}							2		0	H1,M1 [U] {EPa, All}		
Polynesian Storm-petrel	9.3 ± 3.2	1 (6) [U] {EPa}												
Frigate petrels	**9.3 ± 3.2**		**2.5 ± 1.5**						2		0			
Wilson's Storm-petrel	7.8 ± 1.2	3 (56) [U] {Ant, SAt, EPa}					0.28 ± 0.27	1 (M) [U] {All}	0.8 (0.1–1)	0	0	H2,M1,L1 [U] {Ant, All}	1.07 ± 1.06, 1.3 ± 2.1	2 [I, C, M, W] {SAt, NAt}
White-vented Storm-petrel	7.3 ± 0.4	1 (15) [U] {EPa}							2			H1 [U] {EPa, All}		
Grey-backed Storm-petrel											0	M1 [U] {All}		
Oceanites	**7.8 ± 1.5**						**0.28 ± 0.27**		**1.3 (0.1–2)**	**0**	**0**		**1.07 ± 1.06, 1.3 ± 2.1**	

Note: For each species, mean values, uncertainty/range and the number of supporting studies are shown, in addition to the number of birds for speed subparameters and the night flight index, and study quality (High, Medium, Low) for time in the rotor swept zone. A summary of study metadata is provided, showing what phenological stage(s) [I = incubation, C = chick-rearing, M = migration, W = wintering, J = juvenile, U = unknown] and ocean region(s) the calculated subparameter values represent {NAt = North Atlantic, SAt = South Atlantic, Ind = Indian Ocean, NPa = North Pacific, EPa = East Pacific, WPa = West Pacific, Ant = Antarctic, Arc = Arctic, Med = Mediterranean, Nth = North Sea, Crb = Caribbean, All = region not specified in expert opinion/literature review study}. Where a single study informs a species' value, the mean value and uncertainty are as reported by the original study. For taxonomy and scientific names see the Procellariiform flight parameter database (Miller et al., 2025).

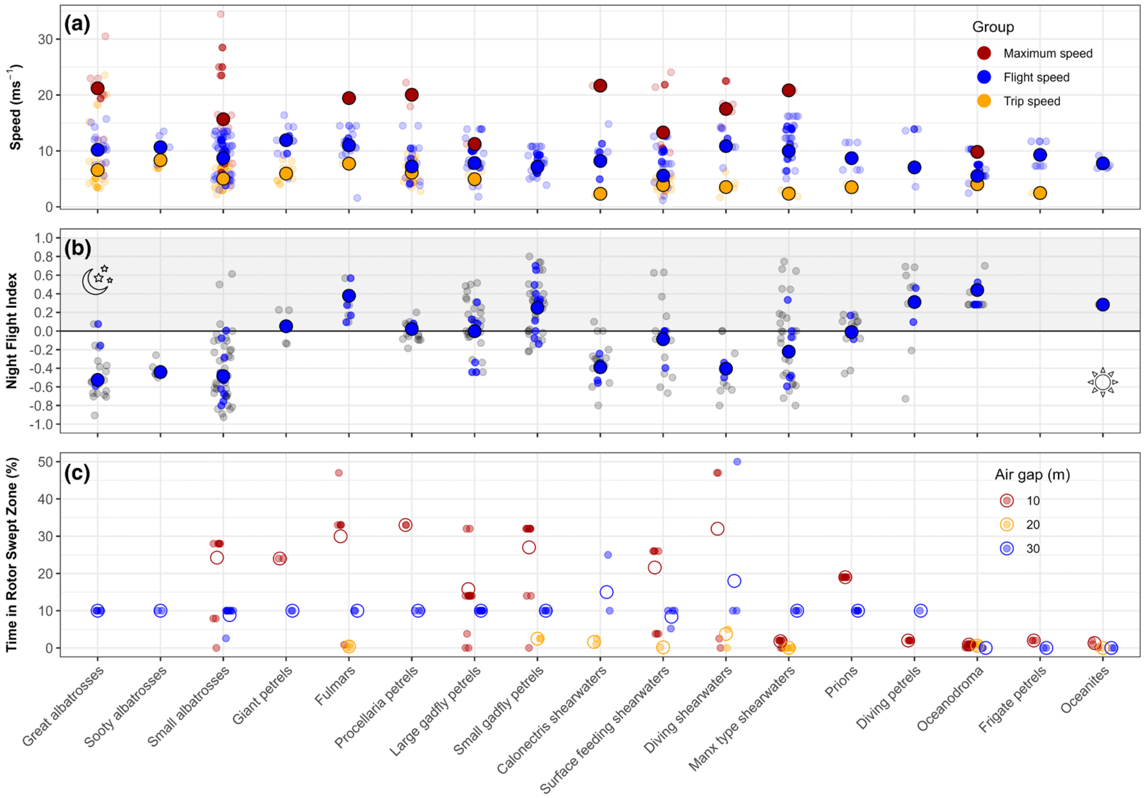

FIGURE 1 Procellariiform flight speeds (a), nocturnal flight activity (b) and time spent in an offshore wind turbine's Rotor Swept Zone (c). Large points show flight group mean, small solid points show species means, and transparent small points show individual effect sizes from literature.

(Figure 3). Only storm-petrel flight groups showed consistent results (from eight studies) of minimal time in the RSZ (Figure 1c) and very low mean flight heights (Figure 3).

4 | DISCUSSION

4.1 | Summary

Our systematic review found sufficient information in the literature to quantify flight speed and nocturnal flight activity for Procellariiform species and flight groups. However, information on mean flight height was too scarce and information on time in the Rotor Swept Zone too uncertain to inform collision risk modelling, representing a key information gap. In the following sections, we discuss Procellariiform flight height, flight speed and nocturnal flight activity, and make recommendations for using our results to inform offshore wind farm collision risk modelling.

4.2 | Flight height

Height information is scarce for Procellariiformes. Eight studies provided data on mean flight heights for 21 species, while 10 studies provided information on time spent in the RSZ for 104 species. This difference in species coverage appears surprising given time in the RSZ relies on flight height information, but can be explained by studies on time in the RSZ relying on literature reviews intended to inform high-level collision vulnerability (c.f. CRM), for which greater uncertainty is acceptable. These literature reviews used different combinations of empirical flight height information, semi-quantitative data, and frequent expert opinion to more broadly describe a greater number of species. Our results highlight the impact of this uncertainty by demonstrating the variability between different studies within flight groups and species (Figure 1a). The uncertainty around reported values of time spent in the RSZ was so great that it masked the effect of increasing turbine air gaps. For example, the Sooty Shearwater *Ardenna grisea* was considered to spend 2.5% of time flying in the RSZ of a turbine with a 10 m air gap (Kelsey et al., 2018), 0%–5% of time flying in the RSZ of a turbine with a 20 m air gap (Robinson Willmot et al., 2013; Wade et al., 2016), and 10% of time flying in the RSZ of a turbine with a 30 m air gap (Reid et al., 2023; Figure S1).

We found very few studies with data on Procellariiform mean flight heights. Studies reported mean flight heights of 0–5 m above the sea surface for all species apart from albatross and giant-petrels, which were reported 0–13 m above the sea surface (Figure 3). These mean flight heights are almost all below the RSZ of offshore turbines, which contrasts with our study-reported results of higher percentage time in the RSZ (e.g. most flight groups spending >10% of time flying in the RSZ of a 10 m air gap turbine; Table 2). Several

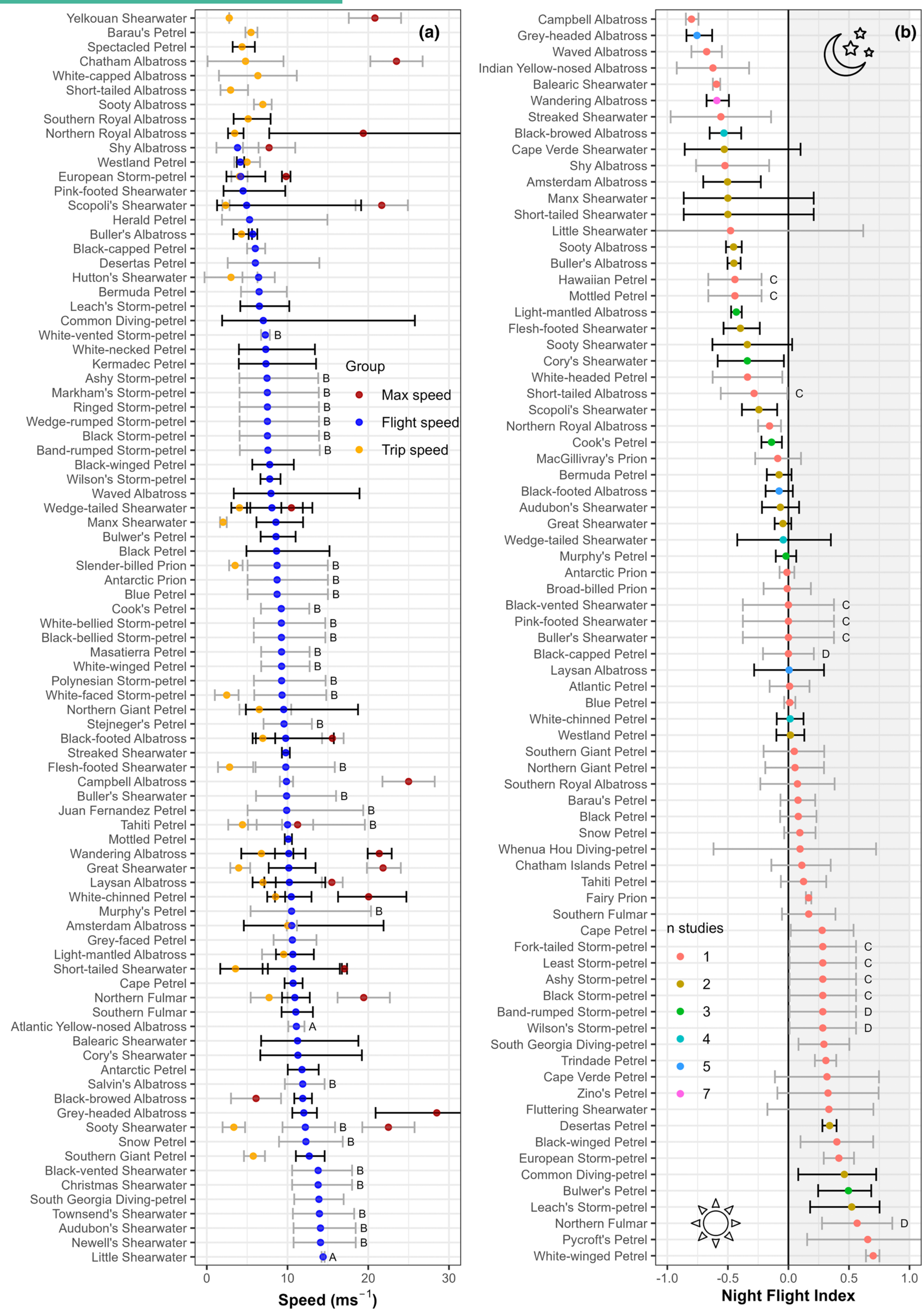

FIGURE 2 Procellariiform mean ± standard deviation flight speeds (a) and nocturnal flight activity (b). Grey error bars denote species values reported by single studies, these are lettered for non-biologger studies: vessel-based surveys, A = Alerstam et al. (1993), B = Spear and Ainley (1997b); and expert opinion/literature review studies, C = Kelsey et al. (2018), D = Robinson Willmot et al. (2013).

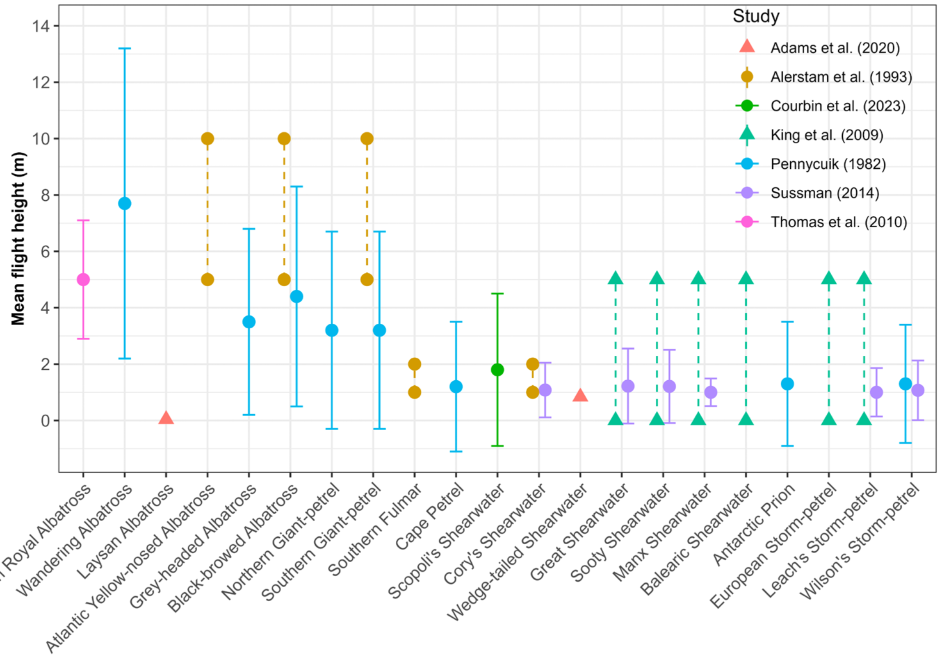

FIGURE 3 Procellariiform mean flight heights reported by studies. Raw study values are shown as either means (circles), with error bars if standard deviation was available, medians (triangles), or ranges (dotted lines).

non-mutually exclusive factors likely explain this disparity. Firstly, as mentioned above, studies on percent time in the RSZ often acknowledge high uncertainty and therefore may take a precautionary approach. For example, Reid et al. (2023) determined that all Procellariiformes apart from storm-petrels spend 10% of time flying in the RSZ of a turbine with a 30 m air gap (Figure S1). Second, most Procellariiformes use dynamic soaring, characterised as cyclical ascent and descent as birds harness wind energy, allowing them to cover vast distances without flapping their wings (Richardson et al., 2018). Consequently, study reporting of mean flight height may significantly underestimate collision risk for dynamic soaring Procellariiformes, and efforts should be made to quantify the upper extremity of the flight height distribution to fully characterise risk. The only information we found in this regard was 'pullup heights' of dynamic soaring albatrosses and petrels between 4.8 ± 2.3 m and 13.5 ± 5 m (Pennycuick, 2002; archived in Miller et al., 2025). Finally, historical vessel survey data and observations of seabird flight height can be more confidently binned into above/below RSZ than used to calculate distributions of flight height or mean flight heights (e.g. Ainley et al., 2015). As such, there are likely volumes of at-sea survey data and experience that inform studies and expert opinions on time spent in the RSZ. Representative of varied Procellariiform phenology, geographical regions and ocean conditions, these underlying survey datasets may more fully characterise Procellariiform risk of collision, for example, observations made in higher windspeeds when Procellariiformes fly higher (Ainley et al., 2015). Therefore, despite the high uncertainty that characterises estimates of percent time in the RSZ, reported values should not necessarily be considered overestimates until quantitative data is available to more objectively assess this.

Collision risk models can receive flight height information in different formats (Band, 2012; Masden & Cook, 2016). For most, a large dataset of absolute flight heights (relative to sea level) is the preferred raw data format. These data come from several platforms, each with limitations: visual boat-based surveys can only operate in fair weather conditions and suffer greater error when estimating flight heights than sensors (Harwood et al., 2018), aerial LiDAR and aerial photogrammetry surveys are also limited to fair weather and can struggle to identify observed bird to species level (Largey et al., 2021), while biologger studies sample smaller numbers of birds and have unique challenges converting GPS altitudes or barometric pressure values to actual flight heights (Johnston et al., 2023). Whatever the platform, raw flight height data are typically converted to proportions of birds or frequency of flights within specified height bands (e.g. 1-metre bands from 0 to 500 m for Band model Options 2 & 3; Johnston et al., 2014), or proportions below RSZ and within RSZ (offshore adaptation of Biosis collision risk model, I. Smales pers. comm). Given our review found very few studies with empirical Procellariiform flight heights, and most of those reported mean flight height instead of a frequency distribution, our results are not useful for parameterising flight height in collision risk models. The only exceptions are Manx Shearwater and Northern Fulmar, for which flight height distributions from Johnston et al. (2014) are available. Alternatively, the 'basic' Band model (known as Option 1) can be parameterised with a simple proportion of birds at collision height (PCH). Our results on percentage time in the RSZ can be interpreted as such; however, we again do not believe the number of studies reviewed or their accuracy are sufficient to sensibly parameterise Band model Option 1.

Although not suitable for parameterising CRMs, our flight height and time in RSZ results may be useful for high-level ranking of Procellariiform collision vulnerability (Garthe & Hüppop, 2004), which can inform early stages of wind farm planning, such as site selection (Bradbury et al., 2014). We suggest our flight-group-aggregated results are most appropriate for this, with the intra-and inter-species uncertainty we highlight also included within rankings (Kelsey et al., 2018; Wade et al., 2016). Despite our results providing the best current synthesis of how high Procellariiforms fly, the lack of data may preclude much differentiation between the collision vulnerability of Procellariiform groups (Figure 1). The only exceptions are storm-petrels, which consistently supported minimal risk of collision, with agreement on 1–2 m mean flight heights and 0.1%–2% time in the RSZ. However, our study has shown that storm-petrels regularly fly at night, and there is evidence that they display light attraction (Deakin et al., 2022). As offshore wind turbines require lighting for navigation purposes, storm-petrels may be attracted towards them at night and become disorientated (possibly circling the light source for hours; Deakin et al., 2022), thereby increasing their risk of collision. This example demonstrates the importance of a deep understanding of Procellariiform ecology for accurate impact assessment and the need for dedicated study on Procellariiform interaction with offshore infrastructure, including potential impact mitigation options (e.g. reduced attraction/disorientation under red lighting; Middlemiss et al., 2025).

4.3 | Flight speed

Our review provides the most comprehensive collation of Procellariiform ground speeds to date. The results broadly agree with predictions of flight speeds of birds based on aerodynamic theory and flight morphology (Pennycuick, 1982; Pennycuick, 1989). Flight group speeds were ranked similarly to theoretical Procellariiform predictions based on wing loading, mediated by their propensity to engage in gliding or flapping flight (Pennycuick, 1982; Spear & Ainley, 1997b). Giant-petrels had the highest flight speed and *Oceanodroma* storm-petrels the lowest, in agreement with their respective highest and lowest Procellariiform wing loading (Spear & Ainley, 1997a). However, some flight groups flew slower than predicted. Great albatrosses flew at their minimum theoretical glide speed, while small albatross and *Procellaria* petrels flight group means were left skewed by some species flying below minimum theoretical glide speed (Pennycuick, 1982; Spear & Ainley, 1997b; Wakefield et al., 2009). In contrast, Manx-type shearwaters and diving shearwaters flew rapidly, utilising their exceptionally [among Procellariiformes] efficient flapping flight (Alerstam et al., 1993; Spear & Ainley, 1997b). Although the Pennycuik (1982) theoretical models provide generally accurate lower and upper Procellariiform speeds, our review included numerous studies where field-observed speeds exceed theoretical bounds, likely due to behavioural factors (e.g. foraging) and the intricacies of Procellariiform flight mechanics (Alerstam et al., 1993; Spear & Ainley, 1997b; Wakefield et al., 2009).

However, some of our flight speed results may be underestimates as we found that the large number of biologger studies included in our review showed significantly lower flight speeds compared to those from vessel surveys. This is most strikingly demonstrated by the surprisingly fast flight speeds of frigate petrels, all sourced from Spear and Ainley (1997b) vessel survey data (Figure 2a). As seabird flight paths are convoluted, flight speed calculated from point-to-point distances decreases with lower sampling frequency (Walker et al., 1995). Typical vessel-based optical and radar sampling frequencies (<30 s; Alerstam et al., 1993) approximate true instantaneous flight speeds, but biologger studies with typical minute to hour sampling frequencies are prone to underestimation (Walker et al., 1995). Underestimates of biologger flight speeds are largest in dynamic soaring species whose zig-zag flight paths are far longer than straight-line distances (Pennycuick, 1982), and in older studies with generally lower sampling-frequency satellite biologgers. As these two factors typically align for albatrosses, it could explain some of the low albatross flight speeds found. Indeed, Wakefield et al. (2009) estimated their hourly Wandering Albatross speeds from GPS biologgers were 6%–20% slower than instantaneous optical or radar survey speeds. Modern GPS loggers can provide 'instantaneous' flight speeds, using Doppler-shift information from movement of the tag relative to the movement of satellites (Safi et al., 2013); however, the GPS studies we reviewed were very poor at reporting whether their flight speeds came pre-calculated by loggers (i.e. Doppler-shift) or were manually calculated from point-to-point distances. A final factor that could additionally bias biologger studies for lower flight speeds is that of tag effects (higher flight costs from carrying biologgers), which have been shown to increase the duration of seabird foraging trips (Bodey et al., 2018) and predicted to increase procellariiform flight costs (Vandenabeele et al., 2012). We strongly recommend that future GPS biologger studies improve estimates of speed accuracy by reporting instantaneous speeds or using point-to-point modelling frameworks that include device error (e.g. Noonan et al., 2019), and that further experimental studies are conducted to confirm differences in flight speeds recorded by vessels and biologgers (i.e. paired observations).

Given the uncertainty above, the influence that flight speed can have on CRMs (Masden et al., 2021), and the physiological link between species in flight groups, we recommend that collision risk models are parameterised with species-specific flight speed values or flight group mean flight speed values. Pragmatism and ecology should inform which of these values are more appropriate in each case. For example, Wandering Albatross flight speed is well-studied so the species value is appropriate, while Shy Albatross *Thalassarche cauta* flight speed is the lowest of any albatross and is derived from a single study, so the flight group mean may be more appropriate. For species with missing flight speeds, we recommend using the respective flight group mean value as a surrogate given the physiological link between species in flight groups, while acknowledging that the flight group may still carry inaccuracy for a given species.

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Maximum flight speeds can be used to parameterise a worst-case scenario in the Band CRM but are scarce for most species, while whole trip speeds represent a significant underestimate and should not be used.

4.4 | Nocturnal flight activity

Our results are in agreement with past research that demonstrates Procellariform species occupy a continuum of baseline nocturnality, from predominantly diurnal flying albatrosses (Phalan et al., 2007) to predominantly nocturnal flying small gadfly petrels (Rayner et al., 2016). Our review found similar baseline nocturnality between species in some flight groups, such as *Procellaria* petrels flying day and night, and storm-petrels flying more at night (Figure 1b). However, for most flight groups, we found high variance between and within species' NFI values. First, this could be a product of summarising species NFI values with groups based on flight physiology, when groups based on foraging ecology may be a more appropriate driver of nocturnality (e.g. Spear et al., 2007). Second, it has been well reported that nocturnality is plastic in Procellariiformes, responding to phenological stage (e.g. more night flight during migration; Bonnet-Lebrun et al., 2021) or foraging opportunities (e.g. availability of prey mediated by the lunar cycle; Dias et al., 2016). In such cases, only meta-analysis of well-sampled species (e.g. Wandering Albatross; Figure 2b) provides a representative estimate of baseline nocturnal flight activity. Nonetheless, the results of our review provide the best current summary of Procellariiform nocturnal flight activity, which is important for parametrising CRMs, and can significantly impact predictions (Furness et al., 2018). For parameterising collision risk models, we recommend using species NFI values in preference to flight group aggregated values due to the high species variance within flight groups. If species NFI values are missing, we recommend using a surrogate value from ecologically similar species rather than using the flight group mean as a surrogate.

Accounting for nocturnal seabird flight in collision risk modelling has traditionally been limited by data availability. Vessel or aerial surveys that count the number of flying seabirds to inform CRMs are only conducted during daylight. To estimate the number of additional collisions from seabirds that may fly at night, a proportion of daytime-estimated collisions is added to represent night-time collisions. Initially termed Nocturnal Activity Factor and ranked from 1 (almost none) to 5 (much; Garthe & Hüppop, 2004), these categories were converted inside CRMs to the proportion of time spent in flight at night relative to the day, ranging from 0 (no flight at night) to 1 (same amount of flight in night and day; Band, 2012; Masden, 2015). What this index does not consider is the possibility that seabirds fly more at night than during the day, which has been demonstrated for several Procellariiformes (Bonnet-Lebrun et al., 2021). We therefore chose to present our results using the Night Flight Index (NFI) of Dias et al. (2012), which varies between −1 (all flight activity occurs in daylight) and 1 (all the flight activity occurs in darkness). To use our NFI values in CRMs that expect a 0–1 range (nocturnal flight equal or below diurnal flight), the conversion NFI + 1 should be used to align indices, and then force models to exceed their upper bound (1) for species that fly more at night than during the day. The commonly used Band CRM spreadsheet (Band, 2012) requires input of Nocturnal Activity Factors (1–5), in which case the conversion ((NFI + 1)/0.25) + 1 should be used. However, the broader question presented by highly nocturnal seabirds is whether a crude multiplier of daytime flight observations is appropriate? Biologgers and new technologies, such as autonomous 3D thermal imaging systems on marine buoys (Schneider et al., 2024), can collect flight data day and night and offer an empirical solution.

4.5 | Importance of site-specific data

Procellariiform flight behaviour varies in response to biotic and abiotic pressures, for example flying more at night during the migratory stage than the wintering stage (Bonnet-Lebrun et al., 2021) or flying faster and higher during times of higher windspeed (Ainley et al., 2015). This is acknowledged by offshore wind farm impact assessment through the collection of site-specific data, which aims to parameterise collision risk models with local flight data (i.e. observations of bird flight within the offshore wind farm footprint) rather than using generic values that broadly characterise each species' flight. Only site-specific data on flight heights are commonly collected, and as this review has found insufficient existing flight height data for Procellariiformes (with the exception of Manx Shearwater and Northern Fulmar; Johnston et al., 2014), we recommend mandatory Procellariiform flight height data collection during baseline surveys for all offshore wind farms outside of northern Europe. If this advice is followed then data from multiple windfarms can be combined to model generic flight height distributions (sensu Johnston et al., 2014) for Procellariiform species, to the benefit of future collision risk assessment and wind farm industry uncertainty.

Collection of site-specific data on flight heights has typically been prioritized over other parameters, such as flight speeds and nocturnal activity, given the sensitivity of CRMs to flight height (Furness et al., 2013) and the ability to collect flight height data during baseline vessel and aerial surveys (Thaxter et al., 2015). However, biologgers and marine buoys with seabird monitoring systems now offer the means of collecting a wider range of site-specific data, providing a more accurate and comprehensive understanding of the local seabird community (Largey et al., 2021; Schneider et al., 2024). For example, some seabirds may migrate through a windfarm footprint with fast, nocturnal flights while others may be highly sedentary during wintering or moulting phases. Furthermore, radar-camera systems can be fitted to turbines, facilitating continued monitoring during wind farm operation and collection of vital data on seabird avoidance rates (Tjørnløv et al., 2023). Considering Procellariiform avoidance rates are virtually unknown, collection of such data should be considered a priority. Facilitated by such technology, future CRMs could be parameterised mainly with site-specific data, providing more accurate quantification of local collision risks. However, until such data become commonplace, the generic CRM parameter values compiled in this study provide an important resource. For example, as of 2025, Australia has the most developed offshore wind industry in Procellariiform-rich waters, with baseline seabird data, including site-specific flight heights, collected (SOTS, 2025). For such projects, our study fills remaining CRM parameter knowledge gaps (flight speed and nocturnality) with best-evidenced values, facilitating more accurate Procellariiform impact assessment, and ultimately better-informed offshore wind farm consenting decisions (Searle et al., 2023).

4.6 | Recommendations

This review has compiled a robust and comprehensive parameter database to support practitioners conducting Procellariiform collision risk modelling for offshore wind farm environmental impact assessment worldwide. For most appropriate use, we conclude with the following recommendations:

- Procellariiform flight height information is scarce. Current published evidence on mean flight height and percentage time in the RSZ is too uncertain to usefully parameterise collision risk models.
- Our results on Procellariiform mean flight height and percentage time in the RSZ aggregated by flight group may be useful for high-level ranking of Procellariiform vulnerability to collision.
- Procellariiform speed information was abundant and sufficient for meta-analyses. We recommend collision risk models should be parameterised with the flight speeds presented here at either species-level or flight group level, as appropriate. Maximum flight speeds, where available, can be used for extreme-scenario parameterisation. Whole trip speeds are an underestimate and should not be used.
- Procellariiform nocturnal flight activity information was also abundant and sufficient for meta-analyses. We recommend collision risk models should be parameterised with species-level NFI values presented in this review.
- For species with missing flight speeds, we recommend using the respective flight group mean value as a surrogate given the physiological link between species in flight groups. For missing NFI values, we recommend using a surrogate NFI value from an ecologically similar species.
- Collection of Procellariiform flight height data will likely become mandatory at prospective offshore wind farm sites. This site-specific data will fill the current knowledge gap for parameterising flight height in Procellariiform collision risk models. Biologging and autonomous monitoring systems can additionally collect site-specific data on flight speed and nocturnal flight activity, providing wind farms with more accurate collision risk estimates than using the generic values compiled here. However, until these data are common, our review provides an important resource.

Whilst this review offers the most complete collation of current and past information, there remain many gaps and uncertainties, and values will change as more data are collected. We offer the above recommendations for impact assessment practitioners (prescribed per species in the Procellariiform flight parameter database; Miller et al., 2025), but encourage ecologically informed and pragmatic discussion about the best parameter values to use.

AUTHOR CONTRIBUTIONS

Mark G. R. Miller, Sara Petrovic and Rohan H. Clarke wrote the manuscript. Mark G. R. Miller and Rohan H. Clarke conceptualised the study. Mark G. R. Miller and Sara Petrovic collected and analysed the data. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

A Procellariiform flight parameter database was constructed from the studies reviewed in this paper. The database includes values extracted from studies with associated metadata, plus meta-analysis results and recommendations for CRM. The database is available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.tx95x6b84 (Miller et al., 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Supplementary methods.

Figure S1. Turbine air gaps considered by studies.

Figure S2. Species-specific flight speeds.

Figure S3. Species-specific maximum speeds.

Figure S4. Species-specific whole-trip speeds.

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