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Altimeters on albatrosses: quantifying flight heights for dynamic soaring seabirds‡

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Research Article

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Summary

Offshore wind farm development is expanding into the Southern Hemisphere, the core range of albatross, petrels and shearwaters (Order Procellariiformes). The risk of collision with offshore turbines is poorly understood for Procellariiformes, primarily because of limited data on how high they fly. Timely filling of this data gap supports decision making with better collision estimates and can embed impact mitigation measures into offshore wind farm design (e.g. increasing turbine hub heights) before construction begins in the Southern Hemisphere. Here, we introduce a new method for flight height estimation in Procellariiformes by recording the characteristic patterns that they exhibit during dynamic soaring flight (cyclical ascent and descent) with bird-borne altimeters. During dynamic soaring flight, Procellariiformes regularly skim the sea surface (altitudes <1 m), which is ideal for setting sea level reference pressure in barometric altitude calculation (here termed altimeter 'zeroing'). We field test our method on breeding Shy Albatross *Thalassarche cauta* in Tasmania, Australia. As proof of concept, we show that albatross-borne altimeters can record fine-scale vertical movements, such as 10 second dynamic soaring cycles, and wave height and periodicity when albatross float on the sea surface. We found agreement between altimeters zeroed with dynamic soaring and GPS altitudes on mean flight heights of c.4 m for Shy Albatross. Altimeters showed a clearer right skew to the flight height distribution, which is crucial for determining how often albatrosses fly at higher altitudes also may be occupied by turbine blades. As a measure of uncertainty, we estimated that altimeter flight heights had a plausible range of 2.1 m between upper and lower scenarios under our method, while GPS altitudes were characterised by high variance around their mean. Our pilot study was limited to three tracked birds and further study is warranted to validate our methods over a broader sample of individuals and environmental conditions. To account for platform-specific error sources, we recommend complimentary use of altimeters and GPS to estimate seabird flight heights. The tiny power demand of altimeters compared to GPS, makes our method attractive for efficient biologger estimation of flight heights in dynamic soaring seabirds (including >100 Procellariiform species).

Introduction

Offshore wind energy supplied 64.3 gigawatts of electricity globally in 2023, and supply is predicted to rise to 563 gigawatts by 2040 (Global Wind Energy Council 2023). Offshore wind farms are an important component of electricity generation portfolios in Europe and East Asia, and now several regions of the southern hemisphere have been identified for development (Weiss et al. 2018). However, offshore wind farms have impacts on the environment, of which collision of birds with turbines is an established risk (Perrow 2019a). The challenge with developing offshore wind farms in the southern hemisphere is that novel environmental impacts may be encountered when local species have no proxies in northern Europe where the bulk of environmental impact knowledge has been developed. Albatrosses, petrels and shearwaters (hereafter, Procellariiformes) are a pertinent example, being predominantly Southern Ocean specialists. Indeed, the only current information on Procellariiform interaction with offshore wind farms (occasionally flying inside wind farm footprints) comes from single shearwater and fulmar species (Deakin et al. 2022), though we note that these species are the focus of targeted research (JNCC 2023; NINA 2025). We are not aware of any recorded Procellariiform collisions at offshore wind farms; however, they have collided with onshore wind turbines (noting their flight differs between land and sea; Hull et al. 2013) and with vessels and oil rigs (noting the influences of light attraction and bad weather; Ronconi et al. 2015; Ryan et al. 2021). Given Procellariiformes include both the most threatened seabird family (albatrosses Diomedeidae; Croxall et al. 2012) and the most numerically abundant seabird family (shearwaters and petrels Procellariidae; Paleczny et al. 2015), there is an urgent need to understand the scale of the threat posed by offshore wind farms against a backdrop of significant other threats (Dias et al. 2019).

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Offshore wind farm threat to seabirds and flight heights

Seabird flight height is one of the most important parameters for estimating collision risk with turbines (Furness et al. 2013; Johnston et al. 2014). The 'minimum tip height' or 'air gap' of a turbine describes the lowest altitude occupied by spinning blades (typically 20–30 m above sea level; Johnston et al. 2014; Reid et al. 2023). Most seabirds fly below the minimum tip height, but some gulls, terns and Sulids (boobies and gannets) regularly fly above it, at potential collision height (Johnston et al. 2014). As such, quantifying the frequency of higher altitude seabird flights is important and flight height distributions (e.g. proportion of birds/flights binned into 1 m altitudinal bands) are preferred over summary values (e.g. mean flight height) for parameterising collision risk models. Little data exists for Procellariiformes; albatrosses have been observed at mean flight heights of 3–8 m (Alerstam et al. 1993; Pennycuick 1982), and all Procellariiformes are thought to fly higher during greater windspeeds (Ainley et al. 2015), potentially increasing collision risk. Filling these data gaps is important as robust seabird flight height data can show how increasing turbine air gaps by building turbine towers taller can reduce collisions (Perrow 2019b). With modern offshore wind turbines capable of 37 m air gaps (Berwick Bank Wind Farm 2021), this represents a simple-to-implement impact mitigation measure when designing new offshore wind farms (Star of the South Offshore Wind Farm 2024).

Seabird flight height data for assessing offshore wind farm collision risk has traditionally come from boat-based visual surveys and digital aerial surveys (Johnston & Cook 2016). Boat-based surveys offer good species-level identification but uncertainty in flight heights estimated by eye whereas digital aerial surveys have poorer species-level identification but more accurate flight height estimation, particularly when using Light Detection and Ranging (LiDAR; ± 1 m accuracy (Cook et al. 2018). However, both survey platforms are limited to operating in fair weather daytime conditions and provide 'snapshots' of flight height – observations made over short periods (seconds) but for many individuals. An alternate and complementary approach would involve sampling flight heights over a longer duration, representative of a range of biotic constraints (e.g. bird phenology) and abiotic conditions (e.g. weather, diel cycle), and may be achieved through the use of bird-borne biologgers.

Calculation of flight height using biologgers

Global Navigation Satellite Systems (GNSS), of which the Global Positioning System (GPS) is the most common, have been used in seabird biologgers since first deployed by Weimerskirch et al. (2002). GPS locations are more accurate in the horizontal plane (<10 m error) than vertical (Lato et al. 2022), and fewer seabird studies have looked at GPS flight altitude than geographical position (Adams et al. 2020; Davies et al. 2024; Johnston et al. 2023; Okado & Watanuki 2023; Ross-Smith et al. 2016). When stationary, vertical mean absolute error in GPS altitude can range between 7–30 m when fixes are taken at low frequency (minutes to hours), but can be improved to 2–7 m when the GPS module does not turn off between successive fixes of several seconds, facilitating higher average satellites per fix and/or the use of inbuilt accuracy filters (Schaub et al. 2023). Furthermore, GPS altitude is calculated relative to a reference ellipsoid or geoid (typically mean sea level), which does not reflect the actual height of a dynamic sea surface that birds fly over. Vertical corrections for tidal movement can be applied (Johnston et al. 2023), but finer scale features such as waves and swell and not easily accounted for. Regardless of fix frequency or geoid correction, vertical observation error associated with GPS altitude in marine studies is assumed to be random and normally distributed (Ross-Smith et al. 2016), noting that in terrestrial studies interactions with landscape elevation and weather can produce non-normal GPS observational error (Péron et al. 2017). Faced with these multiple sources of uncertainty, techniques which can separate process from observational error (e.g. state-space models) provide a powerful tool for estimating GPS flight height distributions (Péron et al. 2017; Ross-Smith et al. 2016).

Barometric altimeters are commonly used in aircraft to measure altitude and have been miniaturised for bird biologging; indeed, their deployment on seabirds precedes deployment of GPS loggers (Nicholls et al. 1994). Altimeter sensors on biologgers have tiny energy demand and have revealed flight height over the sea for swans (Pennycuick et al. 1996), frigatebirds (Clark et al. 2019; Weimerskirch et al. 2004), Sulids (Cleasby et al. 2015; Weimerskirch et al. 2005), pelicans (Shannon et al. 2002), gulls (Johnston et al. 2023) and shearwaters (Courbin et al. 2023). Altimeters calculate altitude by comparing the barometric pressure at height against a known reference pressure, normally at sea level (Péron et al. 2020). However, the relationship does not account for local temperature and pressure changes (e.g. weather), which introduce increasing error with increasing time/distance from the reference pressure sample (Cleasby et al. 2015). The optimal calculation scenario would see barometric pressure measured with a biologger on a flying bird and contemporaneously at the reference elevation immediately below the bird. However, this is unfeasible, and consequently altimeter measures of flight height are only considered more accurate than GPS over short periods of time (minutes to hours) when the weather can be considered constant and the altimeter has been zeroed (provided sea level reference pressure) in that weather (Cleasby et al. 2015; Péron et al. 2020).

As seabirds have only a slim window of flight altitudes (approximately 0–30 m) that are below potential collision height with offshore turbines, accurate estimation of seabird flight heights are paramount. Aerial LiDAR appears to provide the best accuracy but can only operate in fair weather, while current GPS and altimeter biologger approaches sample over a range of biotic constraints and abiotic conditions but with accuracy limitations. To fill this data gap and facilitate informed collision risk modelling at offshore wind farms, solutions providing accurate flight heights representative over a range of conditions are required.

Procellariiform flight height from altimeters zeroed using dynamic soaring

Procellariiformes, such as albatrosses, petrels and shearwaters, utilise dynamic soaring as a flight behaviour to cross vast ocean distances while barely ever flapping their wings (Richardson et al. 2018). Dynamic soaring exploits gravity and the vertical gradient in windspeed of the wind-shear layer at the sea surface and provides 80–90% of the total energy required for sustained soaring in Southern Ocean albatrosses (Richardson 2011). Typical dynamic soaring consists of sequential cycles of 5−15 s (Bousquet et al. 2017; Sachs 2005; Schoombie et al. 2023), within each cycle a bird climbs from close to the sea surface in a wave trough diagonally upwind across the wind-shear layer, upon gaining maximum height it turns c. 90° downwind, descends diagonally across the wind-shear layer into a wave trough, and then turns c. 90° into the wind again (Figure 1; Richardson et al. 2018).

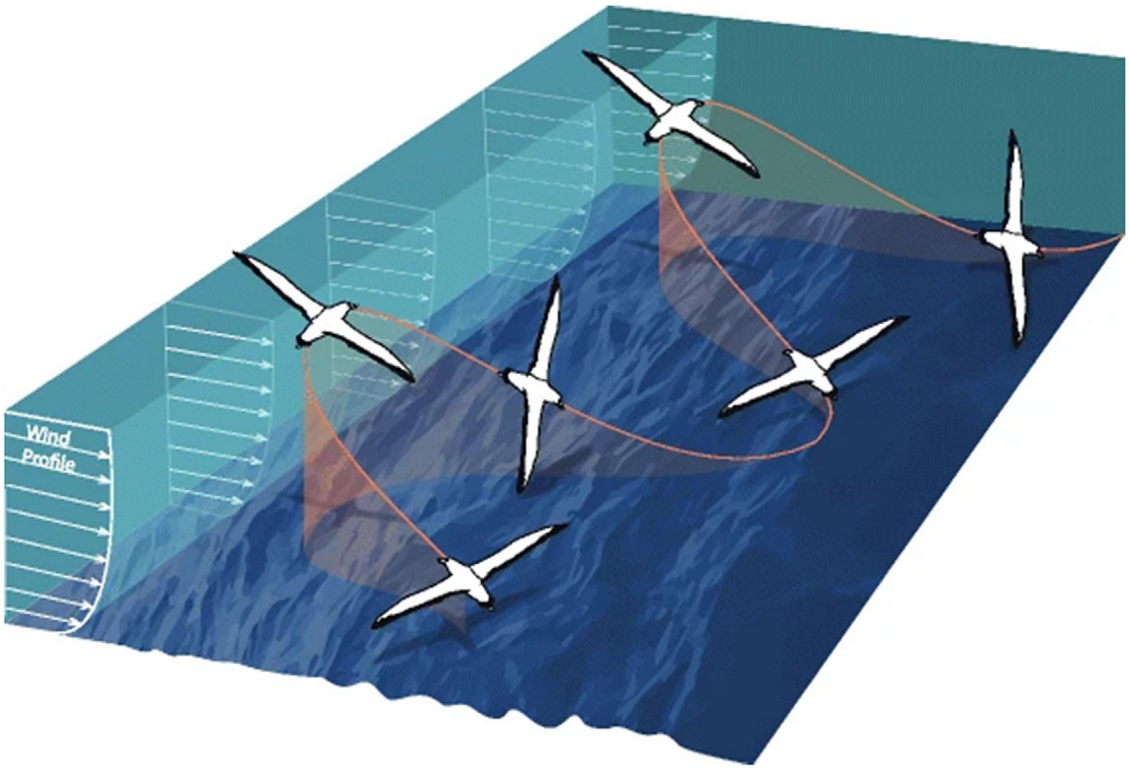


Figure 1. Typical S-shaped dynamic soaring cycles. Schematic shows an albatross flying in an across-wind direction through the vertical wind profile. The bird extracts energy from the wind by climbing headed upwind and descending headed downwind. Image reproduced with permission from (Richardson et al. 2018).

The exact means of energy gain from dynamic soaring remains an area of active research (Kempton et al. 2022; Richardson 2011; Sachs et al. 2012), but theory and observations agree that at the lowest point of typical dynamic soaring cycles albatross are consistently very close (<1 m) to the sea surface (Pennycuick 1982; Richardson 2011; Sachs et al. 2012). We propose to use this "skimming" of the sea surface during the lowest points of dynamic soaring cycles to provide the reference pressure value for altitude calculation using altimeters. This describes a scenario close to optimal altimeter altitude calculation by collecting contemporaneous sea-level reference pressures and pressures at height mere seconds apart and overcomes common altimeter miscalibration associated with short term variation in air pressure associated with the passage of weather systems.

Aims

Here, we introduce a method tailored to address a significant data gap on flight heights in dynamic soaring seabirds such as Procellariiformes. First, we determine whether high sampling-frequency altimeters can be used to detect the vertical magnitude of dynamic soaring cycles. Second, we compare flight heights calculated from altimeters zeroed using dynamic soaring to simultaneously-collected GPS altitudes. Finally, in the absence of independent flight height data, to validate our approach, we compare GPS and altimeter measurements from birds floating on the sea surface to satellite ocean wave data. We use our results to discuss the ability of GPS and altimeter biologgers to measure fine-scale vertical movements in marine conditions and their suitability for seabird flight height estimation.

Methods

Loggers and field attachment

We deployed 11 solar-powered GPS loggers, each with a rear facing barometric pressure sensor and cellular data upload (model ESW400; Cellular Tracking Technologies, LLC, Rio Grande, NJ, USA), on breeding Shy Albatross *Thalassarche cauta* from Albatross Island *namanu rruni* off the northwest coast of Tasmania. Loggers were set to record a burst of 1 Hz data for five minutes ("5-min" hereafter) at the start of each hour. Each 5-min burst recorded 300 datapoints of GPS latitude, longitude and altitude, barometric pressure, ambient temperature and instantaneous speed. Nine loggers were deployed at the start of April 2023 (late chick provisioning phase), and two loggers were deployed in late September/early October 2023 (incubation phase). They were attached to the albatross' mantle feathers using TESA tape and Loctite glue. Each albatross was initially weighed, and deployed loggers (weighing 31–53 g) were less than 3% of the bird's weight.

Track processing and assigning behaviour

We used the track2KBA R package (Beal et al. 2021) to process tracking data into individual trips and remove locations <1 km from the colony. We used the valley of the bimodal distribution of 1 Hz instantaneous GPS groundspeeds as a movement threshold to classify individual latitude-longitude locations as either flying or floating on the sea surface (Weimerskirch et al. 2002). Our identified speed threshold of 4 ms^{-1} (Supplementary materials Figure S1) was in agreement with other albatross studies (Yonehara et al. 2016), and used to assign each 5-min data burst into one of three

behavioural groups: flying (>95% of datapoints with speed >4 ms^{-1}), floating on the sea surface (>95% of datapoints with speed ≤4 ms^{-1}), or take off/landing (<95% dominance of flying or floating datapoints).

Detecting dynamic soaring vertical movements

To proof our proposed use of dynamic soaring to improve altimeter flight height estimation, we first determined whether the vertical component (altitude) of dynamic soaring cycles could be detected via changes in barometric pressure. Given albatross floating on the sea surface can record the vertical magnitude and periodicity of ocean waves with GPS biologgers sampling at 6 Hz (Uesaka et al. 2022), we considered that 1 Hz GPS and barometric pressure sampling should be sufficient to detect the larger vertical magnitude and periodicity of dynamic soaring cycles. To test this, we segmented raw GPS altitude and barometric pressure timeseries into individual dynamic soaring cycles using an automatic timeseries peak detection algorithm in the pracma R package (Borchers 2023). We ran the peak detection algorithm in a similar manner to Schoombie et al. (2023), by first smoothing the time series (3-sample rolling mean) and then specifying a minimum duration between successive dynamic soaring peaks (5 seconds). To further separate out noise, we additionally specified that dynamic soaring peaks were preceded by a minimum of two successive increasing steps and followed by a minimum of two successive decreasing steps. If dynamic soaring cycles were detectable in the data then we would expect resultant dynamic soaring segment durations to fall within published values (5−15 second cycle durations; Sachs 2005, Bousquet et al. 2017, Schoombie et al. 2023). If this was the case for both GPS and pressure timeseries then this was indicative of true detection, given the fundamental differences in between how the two sensors measure vertical height.

Estimating flight height

GPS altitude values were provided by loggers relative to mean sea level. However, we determined from known altitudes at the Albatross Island breeding colony, and instances of birds floating on the sea surface, that all loggers constantly overestimated altitude by an average of 9 m (see Supplementary materials for detail). As per Schaub et al. (2023), we interpreted this as a discrepancy with the geoid model used by the manufacturer and applied a minus 9 m correction to all GPS altitudes.

Altimeters estimate flight height above sea level (h) using the barometric formula (Berberan-Santos et al. 1997):

$$h = -\frac{kT}{mg}\ ln\left(\frac{P}{P_0}\right)$$

where h = altitude (m); k = universal gas constant for air (8.31432 N m mol^{-1} K^{-1}); T = temperature (K) recorded by the logger; m = molar mass of air (0.0289644 kg mol^{-1}); g = acceleration due to gravity (9.80665 ms^{-2}); P_0 = the reference atmospheric pressure (Pa) at sea level (0 m); P= atmospheric pressure (Pa) at height h (m). We propose zeroing altimeters with the lowest points of dynamic soaring cycles, which is when albatrosses the skim the sea surface, to set P_0 in the barometric equation. We are confident that each 5-min data burst contains at least some dynamic soaring behaviour, and therefore low points of cycles at sea level to set P_0, as albatrosses spend 74–95% of flight time dynamic soaring (Conners et al. 2021; Sakamoto et al. 2013; Schoombie et al. 2023) and continuous flapping bouts last on average 1.9 minutes (Conners et al. 2021).

However, the portions of flight spent flapping and the likelihood that not all dynamic soaring cycles conform to the typical theoretical model (e.g. energy for soaring is likely supplemented by updrafts over waves; Richardson et al. 2018) means that we should not assume albatross skim the sea surface every 5–15 seconds (as per typical dynamic soaring). To accommodate this uncertainty around P_0 and its' impact on barometric altitude calculation, we modelled three dynamic soaring scenarios for each 5-min data burst (Figure 2a). An upper scenario assumed that only the highest pressure value within each 5-min burst represented true sea level (P_0) and all other pressure values represented the bird flying some height above sea level. A lower scenario assumed every dynamic soaring cycle skimmed the sea surface, and flight heights were calculated independently for each cycle using the cycle-specific maximum P_0 value. A central scenario was estimated by fitting a Generalised Additive Model (GAM) between the upper and lower scenarios, allowing P_0 a degree of flexibility across each 5-min burst (spline fitted with one knot per minute in the mgcv R package; Wood 2011). GAMs were formulated for each burst separately, using midpoints between upper and lower scenario pressure values as the dependant variable and time as the predictor variable. Fitted values returned by each GAM provided P_0 values for the central scenario. Flight heights were calculated using each of the three scenarios, while the difference between the upper and lower scenarios were used to express the plausible range of flight height estimates under the altimeters-zeroed-with-dynamic-soaring methodology.

An alternative altimeter method for seabirds uses pressure values recorded by birds when floating on the water to set the reference atmospheric pressure for sea level (P_0), allowing recalibration of the barometric equation each time a bird rests (Cleasby et al. 2015). If birds do not float on the water regularly, this method can be further improved by integrating hourly satellite data (Johnston et al. 2023). However, even with satellite data augmentation, there are limitations to how widely the 'floating on water' method can be applied. Considering that our data were collected in hourly 5-min data bursts rather than continuously at 1-second, 10-second, 2-minute or 10-minute interval (Cleasby et al. 2015; Johnston et al. 2023), our ability to regularly record floating bouts was limited. Indeed, 5-min data bursts classified as flying were on average 6.8 (95% CI: 5.4, 8.9) hours from the nearest recordings of floating behaviour (after excluding floating bouts >1 day away; Johnston et al. 2023). Given the decay in the precision of height estimates as the time interval (Δt) between observations of P_0 and P increases (e.g. ±1 m at Δt of 11.5 minutes, while ±7.3 m at Δt of 2.7 hours; Cleasby et al. 2015) due to the effect of weather, atmospheric tides etc, we decided that our data sampling strategy introduced too much error to the 'floating on water' method and it was not used.

Validation of vertical movements from floating birds against satellite wave data

With no independent flight height data available for validation, we instead tested whether the vertical height and periodicity of ocean waves could be accurately estimated from GPS and altimeter sensors. We subset our data to bursts where birds were classified as floating on the water and performed zero-crossing analyses to extract significant wave height (average wave height of the top one-third highest waves) and average periodicity per burst in the

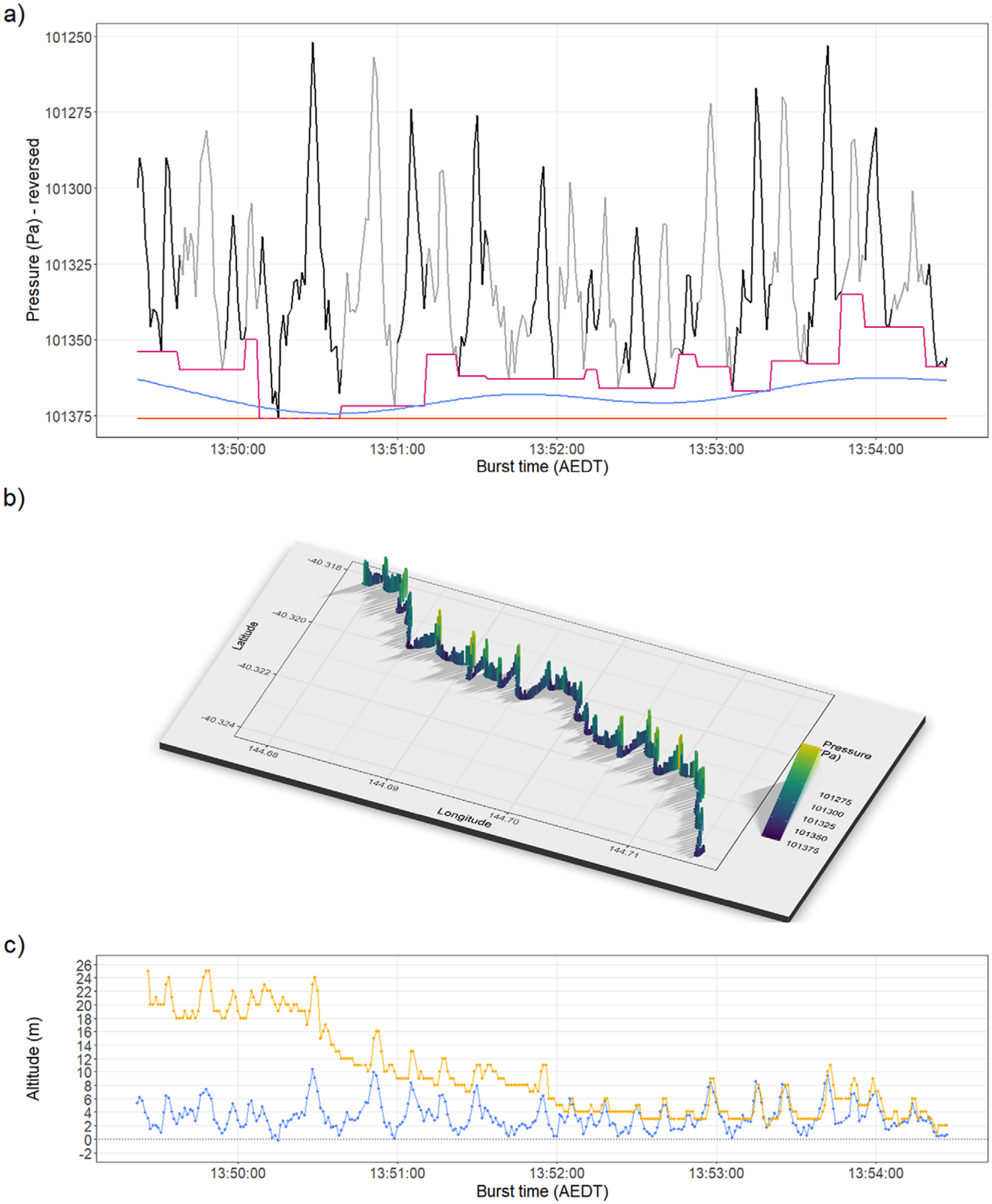


Figure 2. An example 5-min data burst from a GPS-altimeter biologger on a flying Shy Albatross (a) Shows the timeseries of raw altimeter pressure values, with individual dynamic soaring cycles segmented (black-grey alternation). Three lines provide different representations of estimated sea level reference pressure (P_0) for altitude calculation: orange assumes an upper scenario where sea level pressure is provided by the single maximum pressure value; pink assumes a lower scenario where every dynamic soaring cycle meets the sea surface, with its' own P_0 value; and blue shows the central scenario between the upper and lower scenarios, allowing P_0 a degree of flexibility across each 5-min burst; (b) shows the same pressure data as a), visualised with co-sampled GPS locations to show movement in 3D; (c) Shows the same 5-min burst, with central-scenario pressure values converted to altitude above mean sea level (blue), and compared to co-sampled GPS altitude (yellow).

oceanwaves R package (Miller & Neumeier 2021). We then obtained a corresponding value from satellite for significant wave height and average wave periodicity using the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis model 'ERA5'. Hourly ERA5 wave data were available at 30 km spatial resolution and extracted for using the coordinates and timestamp of each burst with the Movebank Env-DATA system (Dodge et al. 2013).

Statistical analyses

All analyses were carried out in R version 4.3.1 (R Core Team 2023). To compare dynamic soaring cycle duration between altimeter and GPS sensors, we used a Mann-Whitney U test. To compare between flight heights from GPS altitude and altimeters, we used paired Wilcoxon tests. To test for agreement between biologger and satellite ERA5 data when estimating ocean wave height and periodicity, we used Pearson's correlations.

Results

Deployment and data return

Of the 11 loggers deployed only three returned data, with durations: 01–04 April 2023 and 01–18 April 2023 (representing late chick provisioning phase); and 29 September–02 October 2023 (representing incubation phase). The three loggers returned 245 5-min bursts of co-sampled GPS-pressure data obtained from birds >1 km from the colony. Of these bursts, we removed 86 that showed erroneous pressure readings consistent with the pressure sensor being submerged or swamped with seawater, and a further three with poor GPS signal (>50% of altitudes >1,000m). Of the remaining bursts we classified 50 as floating on the water, 85 as flying, and 21 as takeoff/landing.

Pressure sensors can detect dynamic soaring

We found clear dynamic soaring cycles occurring simultaneously in raw barometric pressure and GPS altitude timeseries (Figure 2). When plotted in 3D, with co-sampled GPS latitude and longitude, vertical oscillations clearly matched the spatial dynamic soaring cycles. Average dynamic soaring cycle durations recorded by altimeters were approximately half a second longer than those reported by GPS (altimeter 10.4 ± 4.94 s; GPS 9.81 ± 5.08 s; Mann-Whitney-U, W =76,295, P = <0.0001), with both within reported albatross range (5–15 s). GPS altitude struggled to hold a steady reference altitude (e.g. sea level) during bursts. In some, the GPS accuracy appeared to improve over the 5-min burst and flight heights from the two sensors converged in the later minutes (e.g. Figure 2c), but in other bursts GPS altitude fluctuated above and below 0 m for minutes at a time (See Supplementary material Figure S3).

Comparison of flight heights from altimeter and GPS

The central altimeter scenario and GPS altitude agreed on average Shy Albatross flight heights of c.4 m (Figure 3; Table 1). The mean and median flight heights from GPS occurred between the central and upper altimeter scenarios (Table 1), with the median flight heights from altimeters all differing significantly from GPS (paired Wilcoxon: GPS-altimeter lower scenario V = 198,704,999, P = <0.0001; GPS-altimeter central scenario V = 167,397,686, P = <0.0001; GPS-altimeter upper scenario V = 138,154,406, P = <0.0001). GPS flight heights showed high variance around the mean and conformed to a normal distribution, whereas altimeter flight heights showed

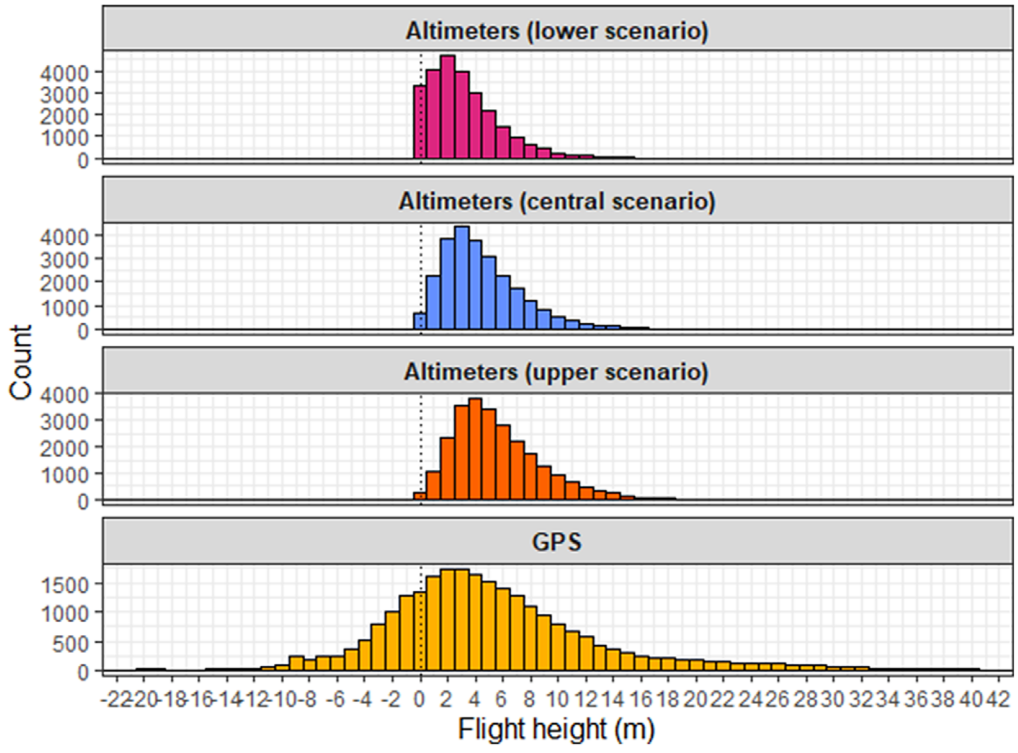


Figure 3. Histogram of flight heights estimated by altimeter and GPS from 5-min data bursts recorded by Shy Albatross while flying.

Table 1. Comparison of summary statistics of flight heights estimated by altimeter and GPS from 5-min data bursts recorded by Shy Albatross whilst flying.

Method	Flight height (m)						Distribution skewness
	Mean (± sd)	Median	Min	Max	25th percentile	75th percentile	
Altimeter (lower scenario)	3.23 ± 2.70	2.67	0	26.1	1.26	4.55	1.46
Altimeter (central scenario)	4.48 ± 2.89	3.91	0	26.1	2.41	5.97	1.23
Altimeter (upper scenario)	5.61 ± 3.24	4.97	0	26.1	3.28	7.32	1.09
GPS altitude	5.10 ± 9.72	4	–63	89	0	9	0.0607

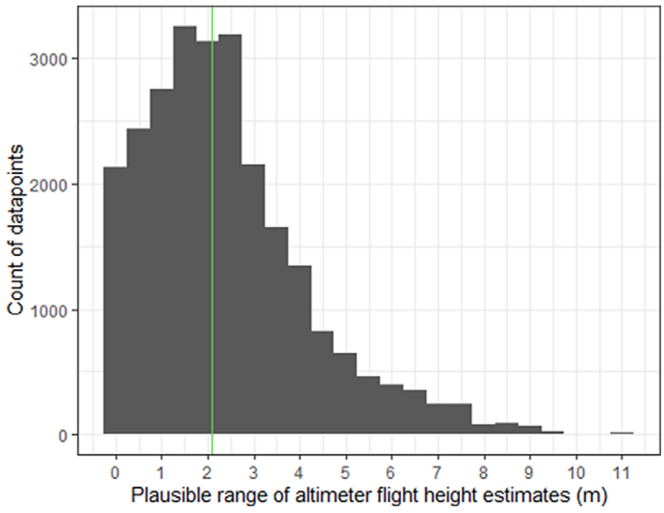


Figure 4. Plausible range of each flight height under the altimeters-zeroed-with-dynamic-soaring methodology. Plausible range is the difference between flight heights from our upper and lower scenarios. Green line shows the median.

lower variances and had right skewed distributions (skewness >1; Table1), due to greater concentrations of datapoints on the left side of their distributions (flight heights <5 m) and longer tails on the right.

As a measure of uncertainty, we calculated the difference in flight heights between the upper and lower altimeter scenarios to give the plausible range (minimum and maximum) for each flight height under the altimeters-zeroed-with-dynamic-soaring methodology (Figure 4). The median plausible range was 2.1 m, varying from 0–10.8 m. We also found some logger-specific variation, with median plausible ranges of 2.6, 2.1 and 1.8 m respectively for the three loggers (Supplementary material Figure S2).

Validation of vertical movements from floating birds against satellite ERA5 wave data

While albatross floated on the sea surface, the vertical signals of waves were clear in altimeter and GPS altitude timeseries (Figure 5a). However, altimeters were better correlated with independent satellite ERA5 data than GPS when estimating significant wave height and wave periodicity (Figure 5b–e).

Discussion

We present the first flight heights from bird-borne altimeters zeroed using dynamic soaring behaviour. This new altimeter method agreed with GPS altitude on average Shy Albatross flight heights of c.4 m, but altimeters showed a clearer right skew to the flight height distribution, important for determining the amount of time spent in higher altitudes also occupied by offshore wind turbine blades. While the three birds tracked in this pilot study may not provide a representative sample of Shy Albatross flight heights, our method is widely applicable to dynamic soaring seabirds (e.g. >100 species of albatrosses, petrels and shearwaters).

We succeeded in our aim of using altimeters to detect the vertical movements of dynamic soaring but demonstrate that high-frequency GPS altitude can also do so. GPS and altimeters use fundamentally different methods to estimate altitude, and their consensus on recording dynamic soaring cycles provides an independent validation of complimentary methods. Further independent validation of the ability of altimeters to detect fine scale vertical movement comes from their measurement of wave height and periodicity while birds floated on the sea surface, which better aligned with satellite ERA5 wave data than GPS altitudes were. The tiny battery requirement of altimeter sensors compared to GPS sensors (Schaub et al. 2023), offers equivalently higher altitude sampling frequencies or longer deployment durations in biologgers.

Seabird flight heights from GPS altitude

The GPS altitudes we recorded were able to clearly track dynamic soaring vertical movements but struggled to maintain a constant altitudinal baseline throughout each 5-min burst, resulting in reported dynamic soaring cycles and wave heights being both above and below sea level (Supplementary material Figure S3). By contrast, GPS biologgers deployed onto floating seabirds by Uesaka et al. (2022) accurately measured wave height, likely facilitated by their 6 Hz sampling rate compared to the 1 Hz rate used here. Improvements in GPS technology, such as new satellite constellations and regional augmentation networks, may yield more accurate GPS altitude (Montenbruck et al. 2017), and future studies should focus efforts on high-frequency sampling (>1 Hz). This would allow improved flight heights to be calculated by subtracting accurate recordings of real sea level height (rather than GPS geoid) when birds float on the water from GPS altitudes recorded when birds fly (e.g. Adams et al. 2020). Our GPS altitude data were normally distributed, with error likely caused by a combination of orbital shifts, satellite clock shifts, and the ionosphere (Olynik et al. 2002), and it should be acknowledged that applicable state-space modelling approaches exist to statistically account for systematic and random GPS error in seabird flight heights (Davies et al. 2024; Johnston et al. 2023; Ross-Smith et al. 2016). These approaches assume true seabird flight heights originate from a log-normal (or similar) distribution, but are observed imperfectly by the GPS biologger. Data on seabird behaviour (e.g. flying/floating) and GPS fix quality (e.g. number of satellites)

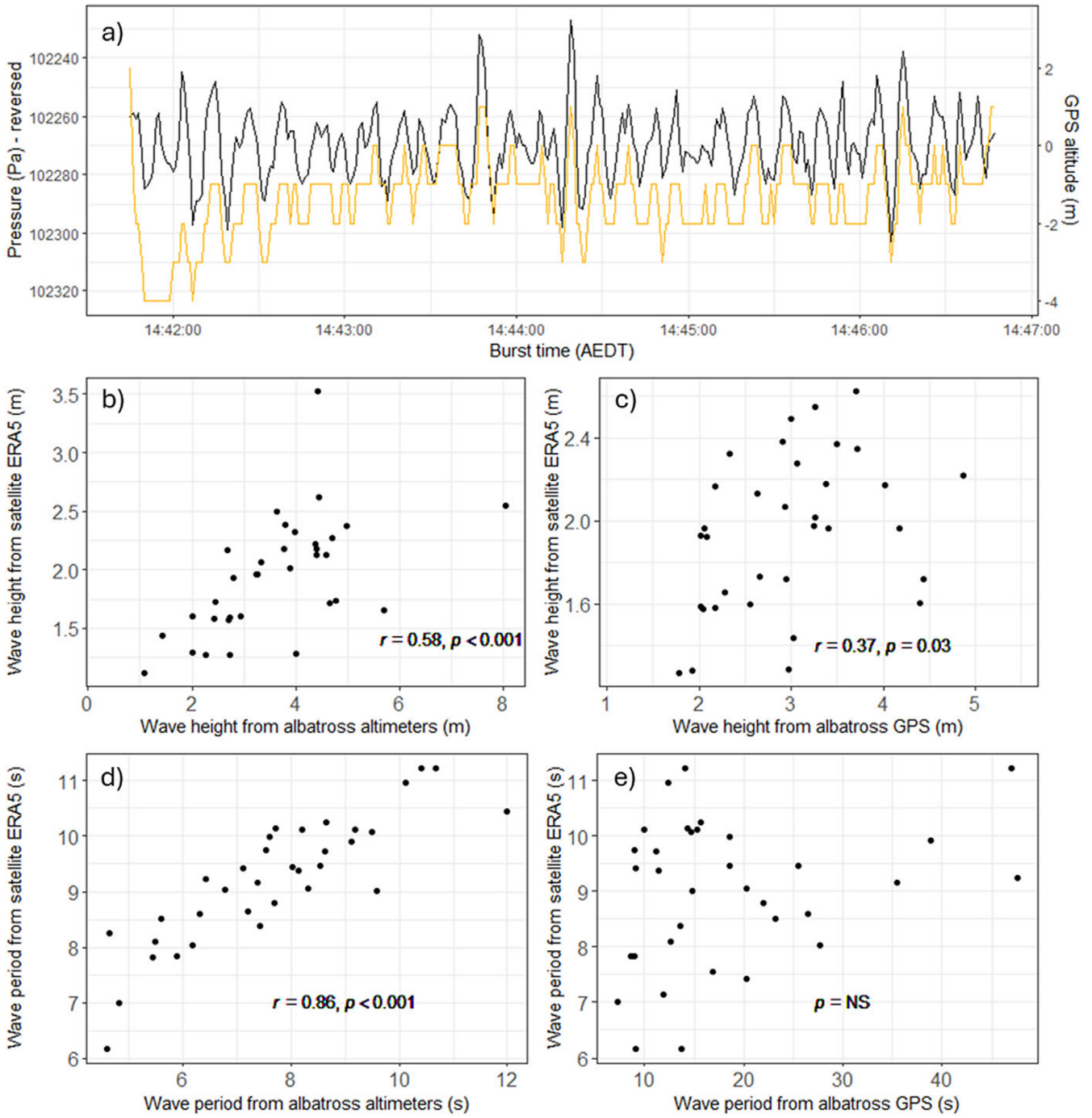


Figure 5. a) Shows an example 5-min data burst recorded by a biologger on a Shy Albatross while it sat on the sea surface. Altimeter (black) and GPS (yellow) timeseries of raw data show recording of ocean waves by both sensors. Subfigures b) – e) show significant wave height and average wave periodicity as estimated concurrently from satellite ERA5 data and from albatross-borne altimeter and GPS sensors.

can be included to account for systematic and random error respectively.

Seabird flight heights from barometric pressure

We have shown that pressure sensors have the ability to record accurate flight heights in dynamic soaring seabirds, validating their accurate measurement of sinusoidal drone movements (Lato et al. 2022). However, pressure sensors are more sensitive to their surrounding environment than GPS (Péron et al. 2020), which can introduce uncertainty into altitude calculation. As a metric of uncertainty, we calculated the typical plausible range of each flight height under our methodology (difference between upper and lower scenarios) as being 2.1 m and consider this to include multiple sources of error. For example, differences in height between an albatross skimming the sea surface at a wave crest compared to a wave trough and differences in albatross orientation relative to logger position - dynamic soarers often roll their bodies

perpendicular to the sea surface, such that back-mounted loggers could be 1.15 m higher than the lower wingtip skimming the sea surface (Shy Albatross mean wingspan of 2.3 m; Hedd 1999). Further error was likely introduced from micro-scale weather and dynamic ocean phenomena, for example occasional 5-min data bursts showed a trend in their baseline pressure as if birds passed through local (c. minute long) pressure gradients (Supplementary material Figure S3-S4). These examples likely contributed to larger plausible range values calculated for some flight heights (Figure 4). Our lower and upper scenarios help understand the scale of altimeter uncertainty associated with our methodology and have potential application (e.g. using upper scenario flight heights under the precautionary principle). However, the methods used to specify these scenarios (automatic segmentation of dynamic soaring cycles) and the central scenario (GAM parameters) could be further refined. We recommend additional research to validate the results of our three-bird pilot study. For example, data collection over a broader sample of individuals and in a wider range of environmental conditions or deployment of altimeter biologgers on drones, equipped with LiDAR for independent, accurate altitude measurement, carefully flown to mimic dynamic soaring. We also note the potential application of state-space modelling approaches developed for seabird GPS data, to also statistically account for multiple error sources in altimeter flight heights (Bogdanova et al. 2021; Johnston et al. 2023).

Procellariiform flight heights and collision risk

Current flight height estimates for Procellariiformes are extremely scarce, with a recent literature review returning only one or two datapoints on mean flight height for 21 species (Miller et al. 2025). Given the sensitivity of collision risk models to flight height (e.g. Lesser Black-backed Gull *Larus fuscus* collision risk modelling using flight heights from altimeters gave 17 more collisions per month compared to flight heights from GPS altitude; Johnston et al. 2023), it is important that not only are Procellariiform flight height data gaps filled, but that they are filled by accurate data. In this regard, our pilot study makes a timely contribution by demonstrating how dynamic soaring flight behaviour recorded by low-power altimeters can produce flight height estimates that are comparable or better than those estimated via GPS, with the method widely applicable to dynamic soaring seabirds (>100 Procellariiform species). Ultimately, altimeter and GPS biologgers should be used complimentarily to overcome platform-specific error sources, and thereby maximise the accuracy of resultant Procellariiform flight heights.

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Data accessibility. Code required to perform analyses is publicly available at: https://github.com/lark-gorilla/flight_heights. The raw tracking data is freely available at Monash Bridges (https://doi.org/10.26180/33829756).

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References

Adams J., Felis J.J. and Czapanskiy M.F. (2020). *Habitat affinities and at-sea ranging behaviors among main Hawaiian Island seabirds: breeding seabird telemetry, 2013–2016*. BOEM Report 2020-006. Camarillo, CA: U.S. Geological Survey. Available at https://espis.boem.gov/final%20reports/BOEM_2020-006.pdf (accessed 01 March 2025).

Ainley D., Prozig E., Zajanc D. and Spear L. (2015). Seabird flight behaviour and height in response to altered wind strength and direction. *Marine Ornithology* **43**, 25–36.

Alerstam T., Gudmundsson G.A. and Larsson B. (1993). Flight tracks and speeds of Antarctic and Atlantic seabirds: radar and optical measurements. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* **340**, 55–67.

Beal M., Oppel S., Handley J., Pearmain E.J., Morera-Pujol V., Carneiro A.P.B. et al. (2021). track2KBA: An R package for identifying important sites for biodiversity from tracking data. *Methods in Ecology and Evolution* **12**, 2372–2378.

Berberan-Santos M.N., Bodunov E.N. and Pogliani L. (1997). On the barometric formula. *American Journal of Physics* **65**, 404–412.

Berwick Bank Wind Farm (2021). *Offshore Environmental Impact Assessment - Appendix 6.1: Scoping Report.* Available at https://berwickbank-eia.com/documents-offshore.html (accessed 01 April 2025).

Bogdanova M.I., Wischnewski S., Cleasby I., Whyte K., Regan C., Gunn C. et al. (2021). *Seabird GPS tracking on the Isle of May, St Abb's Head and Fowlsheugh in 2021 in relation to offshore wind farms in the Forth/Tay region. Report* no 07956. Penicuik: UK Centre for Ecology & Hydrology.

Borchers H.W. (2023). *pracma: Practical Numerical Math Functions. R package version 2.4.4.* Available at https://CRAN.R-project.org/package=pracma

Bousquet G.D., Triantafyllou M.S. and Slotine J.-J.E. (2017). Optimal dynamic soaring consists of successive shallow arcs. *Journal of The Royal Society Interface* **14**, 20170496.

Clark B.L., Handby T., Leat E. and Weber, S.B. (2019). First three-dimensional tracks for the Ascension Frigatebird *Fregata aquila* highlight the importance of altitude for behavioural studies. *Seabird* **32**, 1–19.

Cleasby I.R., Wakefield E.D., Bearhop S., Bodey T.W., Votier S.C. and Hamer K. C. (2015). Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms. *Journal of Applied Ecology* **52**, 1474–1482.

Conners, M.G., Michelot, T., Heywood, E.I., Orben R.A., Phillips R.A., Vyssotski A.L. et al. (2021). Hidden Markov models identify major movement modes in accelerometer and magnetometer data from four albatross species. *Movement Ecology* **9**, 7.

Cook A., Ward R., Hansen W. and Larsen L. (2018). Estimating Seabird Flight Height Using LiDAR. *Scottish Marine and Freshwater Science* **9**, 59.

Courbin N., Besnard A., Boncourt E. and Grémillet D. (2023). *Flight heights of Scopoli's shearwaters* Calonectris diomedea *in the context of offshore wind farm developments* bioRxiv preprint 2023.05.14.540698. Available at http://biorxiv.org/lookup/doi/10.1101/2023.05.14.540698 (accessed 04 January 2025)

Croxall J.P., Butchart S.H.M., Lascelles B., Stattersfield A.J., Sullivan B., Symes A. et al. (2012). Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International* **22**, 1–34.

Davies J.G., Boersch-Supan P.H., Clewley G.D., Humphreys E.M., O'Hanlon N. J., Shamoun-Baranes J. et al. (2024). Influence of wind on Kittiwake *Rissa tridactyla* flight and offshore wind turbine collision risk. *Marine Biology* **17**, 191.

Deakin Z., Cook A., Daunt F., Mccluskie A., Morley N., Witcutt E. et al. (2022). *A review to inform the assessment of the risk of collision and displacement in petrels and shearwaters from offshore wind developments in Scotland.* Scottish Government ISBN 9781805250296. Available at https://www.gov.scot/publications/review-inform-assessment-risk-collision-displacement-petrels-shearwaters-offshore-wind-developments-scotland/ (accessed 04 February 2025)

Dias M.P., Martin R., Pearmain E.J., Burfield I.J., Small C., Phillips R.A. et al. (2019). Threats to seabirds: a global assessment. *Biological Conservation* **237**, 525–537.

Dodge S., Bohrer G., Weinzierl R., Davidson S.C., Kays R., Douglas D. et al. (2013). The environmental-data automated track annotation (Env-DATA) system: linking animal tracks with environmental data. *Movement Ecology* **1**, 3.

Furness R.W., Wade H.M. and Masden E.A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of Environmental Management* **119**, 56–66.

Global Wind Energy Council. (2023). *Global Offshore Wind Report 2023*. Brussels: Global Wind Energy Council. Available at https://www.apren.pt/contents/publicationsothers/gwec-global-offshore-wind-report-2023.pdf (accessed 15 December 2024)

Hedd A. (1999). Foraging ecology of Shy Albatrosses *Thalassarche cauta* breeding in Australia: implications for interactions with longline fisheries. PhD dissertation, University of Tasmania, Hobart.

Hull C., Stark E., Peruzzo S. and Sims C. (2013). Avian collisions at two wind farms in Tasmania, Australia: taxonomic and ecological characteristics of colliders versus non-colliders. *New Zealand Journal of Zoology* **40**, 47–62.

JNCC. (2023). *ProcBe (Procellariiform Behaviour and Demographics).* Available at https://jncc.gov.uk/our-work/procbe/ (accessed 3 April 2026)

Johnston A., Cook A.S.C.P., Wright L.J., Humphreys E.M. and Burton N.H.K. (2014). Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. *Journal of Applied Ecology* **51**, 31–41.

Johnston A. and Cook A.S.C.P. (2016). *How high do birds fly? Development of methods and analysis of digital aerial data of seabird flight heights* (BTO Research Report Number 676), Thetford, Norfolk: British Trust for Ornithology.

Johnston D.T., Thaxter C.B., Boersch-Supan P.H., Davies J.G., Clewley G.D., Green R.M.W. et al. (2023). Flight heights obtained from GPS versus altimeters influence estimates of collision risk with offshore wind turbines in Lesser Black-backed Gulls *Larus fuscus*. *Movement Ecology* **11**(1), 66.

Kempton J.A., Wynn J., Bond S., Evry J., Fayet A.L., Gillies N. et al. (2022). Optimization of dynamic soaring in a flap-gliding seabird affects its large-scale distribution at sea. *Science Advances* **8**, eabo0200.

Lato K.A., Stepanuk J.E.F., Heywood E.I., Conners M.G. and Thorne L.H. (2022). Assessing the accuracy of altitude estimates in avian biologging devices. *Plos One* **17**, e0276098.

Miller L. and Neumeier U. (2021). *oceanwaves: Ocean Wave Statistics. R package version 0.2.0.* Available at https://cran.r-project.org/package=oceanwaves

Miller M.G.R., Petrovic S. and Clarke R.H. (2025). A global review of Procellariiform flight height, flight speed and nocturnal activity: implications for offshore wind farm collision risk. *Journal of Applied Ecology* **62**, 1795–1819.

Montenbruck O., Steigenberger P., Prange L., Deng Z., Zhao Q., Perosanz F. et al. (2017). The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges. *Advances in Space Research* **59**, 1671–1697.

Nicholls D.G., Murray M.D. and Robertson C.J.R. (1994). Oceanic flights of the Northern Royal Albatross *Diomedea epomophora sanfordi* using satellite telemetry. *Corella* **18**, 50–52.

NINA. (2025). *Offshore wind farm wake effects on seabird flight energetics (BIRDWAKE).* Available at https://www.nina.no/english/Sustainable-society/Renewable-energy/BIRDWAKE (accessed 3 April 2026)

Okado J. and Watanuki Y. (2023). Flight altitudes of chick-rearing Rhinoceros Auklets *Cerorhinca monocerata* measured by GPS logger. *Marine Ornithology* **51**, 109–114.

Olynik M., Petovello M.G., Cannon M. and Lachapelle G. (2002). Temporal variability of GPS error sources and their effect on relative positioning accuracy. *Proceedings of the 2002 National Technical Meeting of The Institute of Navigation*, San Diego, pp. 877–888.

Paleczny M., Hammill E., Karpouzi V. and Pauly D. (2015). Population trend of the world's monitored seabirds, 1950-2010. *Plos One* **10**, e0129342.

Pennycuick C. (1982). The flight of petrels and albatrosses (Procellariiformes), observed in South Georgia and its vicinity. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences* **300**, 75–106.

Pennycuick C.J., Einarsson O., Bradbury T.A.M. and Owen M. (1996). Migrating Whooper Swans *Cygnus cygnus*: Satellite tracks and flight performance calculations. *Journal of Avian Biology* **27**, 118–134.

Péron G., Calabrese J. M., Duriez O., Fleming C.H., García-Jiménez R., Johnston A. et al. (2020). The challenges of estimating the distribution of flight heights from telemetry or altimetry data. *Animal Biotelemetry* **8**, 5.

Péron G., Fleming C. H., Duriez O., Fluhr J., Itty C., Lambertucci S. et al. (2017). The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. *Journal of Applied Ecology* **54**, 1895–1906.

Perrow M. (2019a). *Wildlife and Wind Farms - Conflicts and Solutions, Volume* **3**. *Offshore: Potential Effects*. Exeter, UK: Pelagic Publishing.

Perrow M. (2019b). *Wildlife and Wind Farms - Conflicts and Solutions, Volume* **4**. *Offshore:* Monitoring and Mitigation. Exeter, UK: Pelagic Publishing.

R Core Team. (2023*). R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Reid K., Baker G.B. and Woehler E.J. (2023). An ecological risk assessment for the impacts of offshore wind farms on birds in Australia. *Austral Ecology* **48**, 1–22.

Richardson P.L. (2011). How do albatrosses fly around the world without flapping their wings? *Progress in Oceanography*, **88**, 46–58.

Richardson P.L., Wakefield E.D. and Phillips R.A. (2018). Flight speed and performance of the Wandering Albatross with respect to wind. *Movement Ecology* **6**, 3.

Ronconi R.A., Allard K.A. and Taylor P.D. (2015). Bird interactions with offshore oil and gas platforms: Review of impacts and monitoring techniques. *Journal of Environmental Management* **147**, 34–45.

Ross-Smith V.H., Thaxter C.B., Masden E.A., Shamoun-Baranes J., Burton N.H. K., Wright L.J. et al. (2016). Modelling flight heights of Lesser Black-backed Gulls and Great Skuas from GPS: a Bayesian approach. *Journal of Applied Ecology* **53**, 1676–1685.

Ryan P.G., Ryan E.M. and Glass J.P. (2021). Dazzled by the light: the impact of light pollution from ships on seabirds at Tristan da Cunha. *Ostrich* **92**, 218–224.

Sachs G. (2005). Minimum shear wind strength required for dynamic soaring of albatrosses. *Ibis* **147**, 1–10.

Sachs G., Traugott J., Nesterova A. P., Dell'Omo G., Kümmeth F., Heidrich W. et al. (2012). Flying at no mechanical energy cost: disclosing the secret of Wandering Albatrosses. *PLoS ONE* **7**, e41449.

Sakamoto K.Q., Takahashi A., Iwata T., Yamamoto T., Yamamoto M. and Trathan P.N. (2013). Heart rate and estimated energy expenditure of flapping and gliding in Black-browed Albatrosses. *Journal of Experimental Biology* **216**, 3175–3182.

Schaub T., Millon A., De Zutter C., Buij R., Chadœuf J., Lee S., Mionnet A. et al. (2023). How to improve the accuracy of height data from bird tracking devices? An assessment of high-frequency GPS tracking and barometric altimetry in field conditions. *Animal Biotelemetry* **11**, 31.

Schoombie S., Wilson R. and Ryan P. (2023). Wind driven effects on the fine-scale flight behaviour of dynamic soaring Wandering Albatrosses. *Marine Ecology Progress Series* **723**, 119–134.

Shannon H.D., Young G.S., Yates M.A., Fuller M.R. and Seegar W.S. (2002). American White Pelican soaring flight times and altitudes relative to changes in thermal depth and intensity. *The Condor* **104**, 679–683.

Star of the South Offshore Wind Farm. (2024). *Environment Impact Statement (EIS) and Environment Effects Statement (EES) preparation*. Available at https://www.staroftheSouth.com.au/news-media-releases/latest-project-update (accessed 27 June 2024)

Uesaka L., Goto Y., Yonehara Y., Komatsu K., Naruoka M., Weimerskirch H. et al. (2022). Ocean wave observation utilizing motion records of seabirds. *Progress in Oceanography* **200**, 102713.

Weimerskirch H., Bonadonna F., Bailleul F., Mabille G., Dell'Omo G. and Lipp H.-P. (2002). GPS Tracking of Foraging Albatrosses. *Science* **295**, 1259–1259.

Weimerskirch H., Le Corre M., Jaquemet S., Potier M. and Marsac F. (2004). Foraging strategy of a top predator in tropical waters: Great Frigatebirds in the Mozambique Channel. *Marine Ecology Progress Series* **275**, 297–308.

Weimerskirch H., Le Corre M., Ropert-Coudert Y., Kato A. and Marsac F. (2005). The three-dimensional flight of Red-footed Boobies: adaptations to foraging in a tropical environment? *Proceedings of the Royal Society B: Biological Sciences* **272**, 53–61.

Weiss C.V.C., Guanche R., Ondiviela B., Castellanos O.F. and Juanes J. (2018). Marine renewable energy potential: A global perspective for offshore wind and wave exploitation. *Energy Conversion and Management* **177**, 43–54.

Wood S.N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric Generalized Linear Models. *Journal of the Royal Statistical Society Series B: Statistical Methodology* **73**, 3–36.

Yonehara Y., Goto Y., Yoda K., Watanuki Y., Young L.C., Weimerskirch H. et al. (2016). Flight paths of seabirds soaring over the ocean surface enable measurement of fine-scale wind speed and direction. *Proceedings of the National Academy of Sciences* **113**, 9039–9044.