- (Ö)



SI Figure 5

SI Figure 8

Fig. 5. Wandering albatrosses tend to search perpendicular to the wind. (*A*) Circular histogram plot of flight bearings relative to wind direction for 55 flight segments. Bearings are normalized such that upwind is zero degrees. (*B*) Sample track illustrating how birds maintain crosswind flight after a change in the prevailing wind direction. The open circles indicate separate feeding events, and the arrows crossing them indicate the associated wind vector. Vertical and horizontal scale bars in the lower right-hand corner refer to the dimensions of the smallest squares on the background grid.

SI Figure 6

Fig. 6. Circular vector plots of linearity versus approach bearing relative to wind for all in-flight approaches (A), direct approaches (B), and turn/zigzag approaches (C). Plots are normalized such that upwind is zero degrees in each graph. The outer circle represents a linearity of 1. Direct approaches were significantly more linear for crosswind flight, but there was no correlation between linearity and relative approach bearing for turn/zigzag approaches.

SI Figure 7

Fig. 7. Daytime and nighttime variation for each approach type with respect to the average mass of prey captured (*A*) and the number of prey items caught (total = 153) (*B*). In each graph, black bars indicate nighttime activity and white bars indicate daytime activity. Values are expressed as mean ±SE.

SI Figure 8

Fig. 8. Daytime and nighttime in-flight foraging activity relative to the lunar cycle. White bars indicate daytime activity and black bars indicate nighttime activity. Data are expressed as relative percentages of events observed during the lunar phase indicated by the icon below each pair of bars. Numbers above each bar indicate the number of prey capture events for that category. Asterisks indicate P < 0.05.

SI Text SI Results

Wandering Albatrosses Use Different Approach Types

Neritic versus oceanic. Approach types occurred with equal frequency over neritic and oceanic waters (direct approaches: n = 43, $c^2 = 1.145$, P = 0.285; turn/zigzag approaches: n = 39, $c^2 = 3.145$, P = 0.076; circle approaches: n = 5, $c^2 = 1.93$, P = 0.165; water approaches: n = 78, $c^2 = 0.462$, P = 0.497). The mass of prey items captured over neritic waters versus oceanic waters was equivalent [direct approaches: n = 36, S = 313.0, Z = -0.0317, P = 0.975; turn/zigzag approaches: n = 36, S = 213, Z = -0.889, P = 0.374; water approaches: n = 76, S = 1218, Z = -0.9457, P = 0.3443, Mann-Whitney (Wilcoxon rank sign) test]. For circle approaches, sample size was insufficient for analysis.

Wind speed and approach flight speed. We found that birds approached prey items at a wide range of wind speeds, from 2.13 to 20.0 m/s (7.6 to 72 km/h), and, on average, 10.45 ± 0.41 m/s (37.6 ± 1.5 km/h). Wind speed was slightly lower for circle approaches (6.67 ± 1.22 m/s, 24.0 ± 4.39 km/h), but there was no difference among in-flight approach types with respect to wind speed (one-way ANOVA, $F_{3,82} = 2.117$, P = 0.104). Average flight speed was similar across all in-flight approach types (direct: 10.58 ± 1.18 m/s; turn: 10.44 ± 1.28 m/s; zigzag: 13.97 ± 0.65 m/s; and circle: 12.32 ± 2.65 m/s) (one-way ANOVA, $F_{3,65} = 1.09$, P = 0.359).

Linearity and Wind

Further analysis of the linearity of upwind flight. We examined whether linearity of the approach varied with wind speed by considering only upwind approaches. For this analysis, we selected approaches that started within a cone of $\pm 45^{\circ}$ up to 10 km downwind of the prey capture point, irrespective of approach shape. Of 27 such approaches, 7 were direct, 11 turned, 7 zigzagged, and the remaining 2 circled. Linearity ranged from 0.061 (sinuosity 16.460) to 0.98 and wind speed ranged from 2.3 m/s (8.3 km/h) to 18.0 m/s (65.0 km/h). There was no correlation between linearity and wind speed (all flown approaches: n = 27, r = 0.071, P = 0.726; direct: n = 7, r = 0.047, P = 0.92; turn and zigzag: n = 18, r = -0.33, P = 0.181). The approach with the highest wind speed had a mid-range linearity of 0.58 (sinuosity 1.72), and the approach with the lowest wind speed had a relatively low linearity of 0.23 (sinuosity 4.34). These measures confirm that, even among the upwind flown approaches, birds used flight patterns of differing shapes (direct, turn, zigzag) and linearity, largely independent of wind conditions, suggesting that the characteristics of upwind flown approaches are not systematically determined by the wind as is commonly assumed.

Daytime Versus Nighttime Foraging

Foraging by moonlight. Because data were not balanced across the lunar cycle, we examined proportions of daytime and nighttime foraging for each phase of the lunar cycle. We found that there was proportionally more daytime than nighttime foraging during new and crescent moons but not during quarter, gibbous, or full moons (new moon: n = 7, df = 1, c² = 3.96, P = 0.0465; crescent: n = 31, c² = 5.62, P = 0.0177; quarter: n = 9, c² = 0.1113, P = 0.7386; gibbous: n = 29, c² = 0.31, P = 0.5771; full: n = 11, c² = 2.36, P = 0.1246).

Wind speed. Prey items were caught at wind speeds ranging from 2.13 to 20.0 m/s (7.6 to 72 km/h), with average speeds of 10.45 ±0.41 m/s (37.6 ± 1.5 km/h). We found no significant correlations between wind speed and the mass of prey items captured for any of the in-flight approach types, although water approaches showed a strong positive trend (all in-flight approaches: n = 77, r = -0.166, P = 0.149; direct: n = 36, r = 0.194, P = 0.256; turn/zigzag: n = 36, r = -0.177, P = 0.301; circle: n = 5, r = 0.4, P = 0.5; water: n = 76, r = 0.219, P = 0.0574; Spearman rank correlation). All prey items over 1 kg were caught in medium wind speeds within the range of 5.2 to 9.9 m/s (18.7 to 35.6 km/h).

SI Methods

Field Instrumentation

Instrumentation. Birds were caught by hand, weighed, and instrumented as they were about to leave the colony to forage such that birds were not generally disturbed on the nest site. Birds typically took off within minutes after being instrumented. Once the bird returned from its foraging trip, the equipment was retrieved and the bird was again weighed. No chick desertion or other deleterious impact to breeding or fledging success was observed, and trip duration was similar to uninstrumented birds (»3 days, see ref. 1). The age, sex, and previous breeding experience of each bird used in this study was documented as part of an ongoing, long-term database (2). Both the GPS unit and the recorder were fixed to the back feathers of the bird y using tesa tape to minimize handling stress (1, 3) and to allow recovery of the recording devices without injury or damage to feathers (4).

GPS units and stomach temperature recorders. GPS units (New Behavior; 45 g, see ref. 5) were programmed to record one location (\pm 5 m) every 10 s. To record data related to foraging events (i.e., the time at which prey items were swallowed and the mass of prey items swallowed), birds swallowed a 20-g Stomach Temperature Pill, which transmits changes in stomach temperature to a recorder every 15 s (Wildlife Computer; see ref. 6 for a description of how the prey mass is estimated). The total weight of the equipment was 90 g, which is less than 1.5% of body mass, and well below the accepted 3-5% threshold for adverse behavioral effects (7). GPS data were downloaded and filtered as previously described (1).

Data processing. As with previous studies (3), birds were considered to be sitting on the water if their speed

of movement dropped below 2.8 m/s (10 km/h) between three consecutive locations, as birds cannot stay airborne at such slow speeds. Data from stomach temperature recorders were analyzed by using Software MT (Jensen Software), which uses the rapid drop in stomach temperature as an indicator of both timing of a feeding event and mass of the prey captured. The mass of the prey captured is determined by using the integral of a precipitous drop followed by an exponential rise in temperature (PDER; see ref. 6). As part of an earlier study (1), ingestion of prey was discriminated from ingestion of water or jellyfish on the basis of the characteristic shape of the PDER, such that water ingestion events could be excluded from further analysis. GPS location data were subsequently combined with prey ingestion data to determine the location of a feeding event.

Data Analysis

Categorization of approach types. Tracks were created from points by using the "Point to Polyline" function of the ET GeoWizards Toolkit (www.ian-ko.com). Compression or recording errors were identified by eye (as successive, identical relative offsets that appear as diagonal lines) and excluded from analyses as appropriate.

Wind direction and speed. Wind direction and speed values used in the analysis were the most detailed available. The data product consisted of longitudinal and latitudinal wind strength components on a grid spaced at 0.25°, produced twice daily at 6 a.m. and 6 p.m. local time (Coordinated Universal Time, UTC, + 4). For consistency, the data from the time and grid point closest to the feeding event were used to derive wind direction and strength values, which were assumed to remain constant over the entire 0.25° grid cell (»18-28 km depending on latitude) and 12-h period. Missing data were filled in by linearly interpolating from the nearest available surrounding cells of the same time.

Linearity. Distances were calculated by using the haversine method, which operates on geographic coordinates in decimal degrees and returns a distance in meters. We used the following simplified formula, which was verified to produce results accurate to within 5% of ArcGIS measurements made by hand:

Dlon = Lon2 - Lon1

Dlat = Lat2 - Lat1

AvgLat = Average(Lat1,Lat2)

Req = 111134

Distance = sqrt(power(Req*(Dlat),2) + power(Req*cos(radians(AvgLat))*(Dlon),2))

Discussion

Little is known about visual sensitivity (or the ability to see contrast) among the procellariiforms (for exceptions, see ref. 9) and these are areas that need to be more fully explored (for other aspects of procellariiform vision, see refs. 10 and 11).

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Abstract

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