

THE SIGNIFICANCE OF GROUND EFFECT TO THE AERODYNAMIC COST OF FLIGHT AND ENERGETICS OF THE BLACK SKIMMER (*RHYNCOPS NIGRA*)

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SUMMARY

The kinematics and aerodynamics of flapping and gliding flight by the black skimmer were investigated to evaluate the significance of ground effect to the foraging and daily energy budget of skimmers. Ground effect is an increase in lift and decrease in drag of an aerofoil when close to the ground.

The duration of upstroke and downstroke, the wing movements and the pronation/supination of the wings during flapping flight of the skimmer are similar to other birds. Wing-beat frequency was 3.1 s^{-1} and flight velocity was 9.1 m s^{-1} . The wing stroke was markedly asymmetric, with the majority of the stroke occurring above the plane of the body. During skimming, wing beats are intermittent and of low amplitude; flight velocity is 10.3 m s^{-1} .

Induced power, parasite power and profile power of skimmers were calculated after Tucker (1973) in the absence of ground effect, and the glide angle and sink velocity were calculated for gliding skimmers. Ground effect was shown to markedly reduce induced power requirements, and hence total power requirement, of flapping flight, and reduce the glide angle and sink velocity during gliding.

The hydrodynamic drag of the lower mandible was estimated to be 10^{-4} N, which is insignificant compared to the total aerodynamic drag (0.4 N).

Ground effect was shown to markedly increase foraging efficiency and facilitate the attainment of a positive daily energy balance. The significance of ground effect to other flying vertebrates was discussed.

INTRODUCTION

Skimmers, family Rhyncopidae (Charadriiformes), are so-named because of their unusual mode of feeding. They catch their prey exclusively by skimming, i.e. flying or gliding very close to the surface of a calm body of water, with the lower mandible submerged in the water. Prey, such as small fish and crustaceans, are eaten in flight (Davis, 1951; Tomkins, 1951; Zusi, 1962).

This unique feeding technique has certain aerodynamic and hydrodynamic consequences. The total arc through which the wings may be beaten is diminished when the bird is close to the water surface, hence aerodynamic power generation is

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potentially reduced. The bird experiences an additional drag when skimming due to the immersion of the beak, and occasionally the feet and wing tips, in the water. Diminished lift and augmented drag would be expected to adversely affect the aerodynamic performance of skimmers. However, behavioural observations indicate that this is not so; skimmers can glide for considerable distances while feeding, with only intermittent and low-amplitude wing beats (Zusi, 1962; personal observations). We show that the aerodynamic performance of skimmers is influenced by ground effect, which has a profound influence upon the energetic balance of skimmers. Ground effect is an increase in lift, and decrease in drag, which occurs when an aerofoil is in close proximity to the ground (Reid, 1932).

METHODS

Black skimmers (*Rhyncops nigra*) were observed at the Salton Sea, Imperial County, California, and photographed with a Beaulieu 16 mm cine camera at 64 frames s^{-1} . The film speed was calibrated with a Strobotac 1531-A stroboscope. The films were projected on to a ground-glass screen for frame-by-frame analysis of wing and body movements during flapping and skimming flight. Relative flight velocities were calculated as the distance moved by the bird per frame relative to the length of the lower mandible, and were converted to absolute velocities by assuming that the lower mandible was 10 cm long. Wing-beat frequency was determined from the number of frames elapsed per wing stroke.

Dimensions of the upper and lower mandibles, length, chord and thickness (see Fig. 1) were measured for ten specimens of *R. nigra* from the Donald R. Dickey Collection, UCLA, with vernier calipers accurate to ± 0.1 mm.

The hydrodynamic drag of the lower mandible was measured with the mandible submerged 3 cm in a water channel at a flow rate of 0.59 m s^{-1} . Drag forces were measured with a calibrated strain-gauge and recorded with a Gilson polygraph.

Silicone rubber casts (RTV Silastic) were made of the mandibles and were cut in transverse sections to determine the local cross-section of the mandibles.

RESULTS

Morphometrics

The lower mandible is normally longer than the upper, and is considerably more streamlined (Fig. 1). The dimensions of the mandibles of ♂ and ♀ skimmers are summarized in Table 1. The mean aspect ratio (length/chord) of the upper and lower mandible was 10. The mean thickness ratio (thickness/chord) was 0.60 for the upper and 0.17 for the lower. The rhamphotheca (the blade) of the lower mandible, and to a lesser extent the upper rhamphotheca, are covered with small ridges (approx. 4.8 ridges/cm) which are at an angle of about 45° to the leading edge (Fig. 1). The ridges at the centre of the lower rhamphotheca are about 0.01 cm high (0.6% of the local chord), and the height ranges from 0% at the tip to 1.5% at the base. The local cross sections of the lower and upper rhamphothecae are shown in Fig. 1.

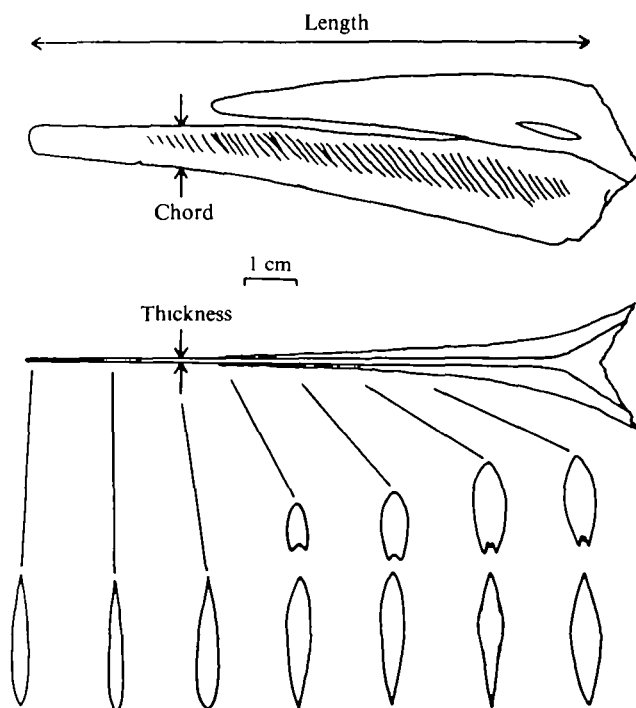


Fig. 1. Lateral and ventral views of the mandibles of the black skimmer, with cross-sections of the upper and lower rhamphothecae.

The wing lengths of specimens of *R. nigra* in the Dickey collection were about 38 cm (♂) and 34 cm (♀) (Table 1). No body weights were available for these specimens, but typical values are 3.43 N (♂) and 2.35 N (♀) (Zusi, 1962).

Kinematics

Flapping flight

The upstroke and downstroke of the wings during forward, horizontal flight are shown in Fig. 2. Wing-beat frequency had a mean value of 3.1 s^{-1} (s.e. = 0.1 , $n = 12$) and mean flight velocity was 9.1 m s^{-1} (s.e. = 0.1 , $n = 7$). Upstroke was faster than downstroke (38% versus 62% of time respectively) and the wings were more pronated during downstroke (Fig. 2). The wing stroke was also asymmetric with respect to the horizontal plane of the body, with the wing tips moving about 45° above and 15° below the plane of the body (Fig. 2). The wing tips were above the plane of the body 65% of the time during each wing stroke, and below it 35%.

Skimming flight

Skimming was typically a glide interspersed with intermittent wing beats of low amplitude (Fig. 3). The body was normally horizontal, or inclined slightly downward, with the head 8–10 cm above the water surface. The wing tips were often closer to, and occasionally touched, the water. The tail was occasionally spread, particularly

Table 1. *Beak and wing morphometrics of black skimmers*
(all values are cm)

	Males ($n = 4$)	Females ($n = 6$)
Lower mandible		
Length	10.8 \pm 0.15	8.3 \pm 0.13
Tip chord	0.57 \pm 0.01	0.53 \pm 0.03
Base chord	1.55 \pm 0.04	1.26 \pm 0.02
Tip thickness	0.06 \pm 0.01	0.05 \pm 0.01
Base thickness	0.33 \pm 0.01	0.27 \pm 0.01
Upper mandible		
Length	8.34 \pm 0.02	6.95 \pm 0.08
Tip chord	0.23 \pm 0.02	0.22 \pm 0.01
Base chord	1.37 \pm 0.04	1.10 \pm 0.02
Tip thickness	0.08 \pm 0.01	0.05 \pm 0.01 ^a
Base thickness	0.76 \pm 0.01	0.60 \pm 0.03
Wing length	38.1 \pm 0.93	34.1 \pm 1.03

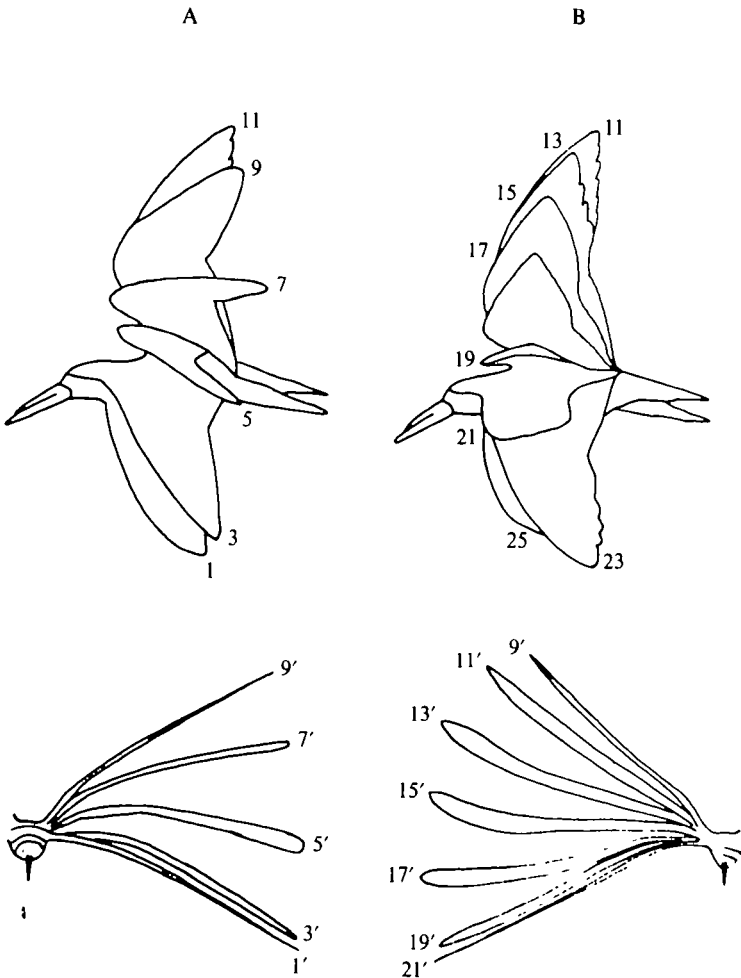


Fig. 2. Wing positions of the black skimmer during upstroke (A) and downstroke (B). Numbers indicate frames elapsed since beginning of upstroke (1 frame = $\frac{1}{25}$ s). Prime notation for frontal views indicate that they were determined for a different film sequence than the lateral views.

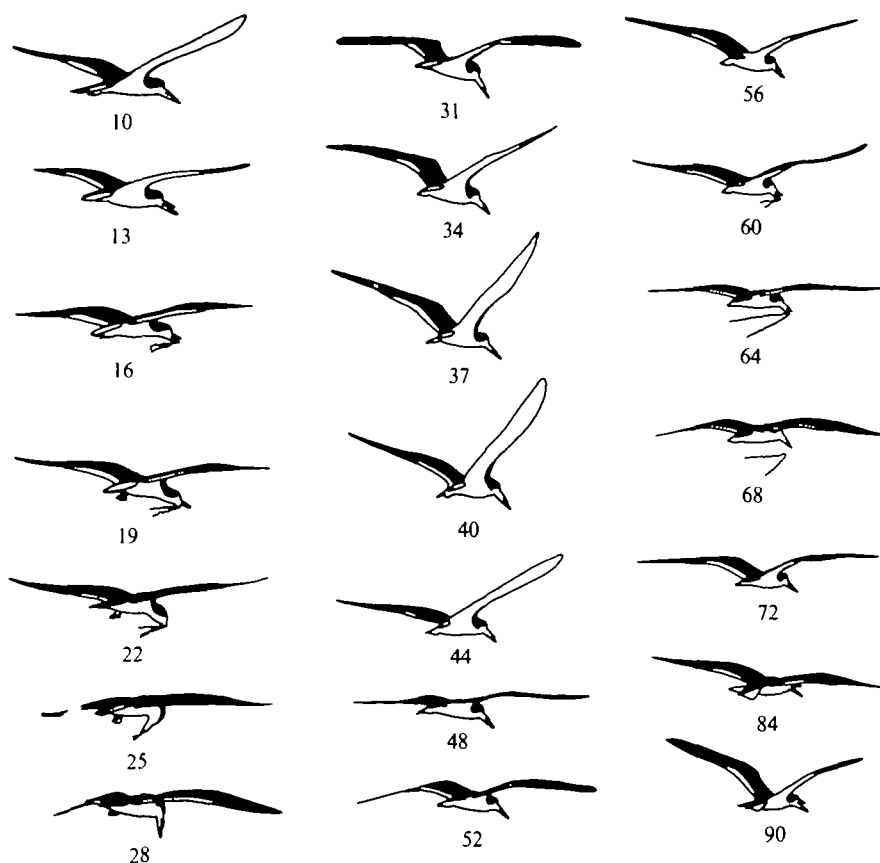


Fig. 3. Black skimmer during feeding activity. Numbers indicate frames elapsed since first view (1 frame = $\frac{1}{40}$ s).

when a prey item was taken (Fig. 3). The feet, which were normally folded under the body during flapping and skimming flight, were sometimes lowered during skimming and even dragged through the water. When wing beats occurred during skimming, their frequency was about 3.7 s^{-1} on average ($n = 4$). The mean value for flight velocity was 10.3 m s^{-1} (S.E. = 2.5 , $n = 4$). The lower mandible intersected the water surface at an angle of about 45° .

AERODYNAMIC ANALYSES

Flapping flight

The power expended in forward, horizontal flight of fixed-wing aircraft, helicopters, and birds must overcome induced, parasite and profile drag (see Pennycuik, 1969, 1972 1975; Tucker, 1968, 1973, 1974; Greenwalt, 1975; Dommasch, Sherby & Connolly 1969; Gessow & Myers, 1952). Lift, which supports the weight of the bird, is an upward force due to the downward flow of air which is induced by the aerofoil (wings). Induced drag (D_i) is the drag force associated with the deflexion of air downwards

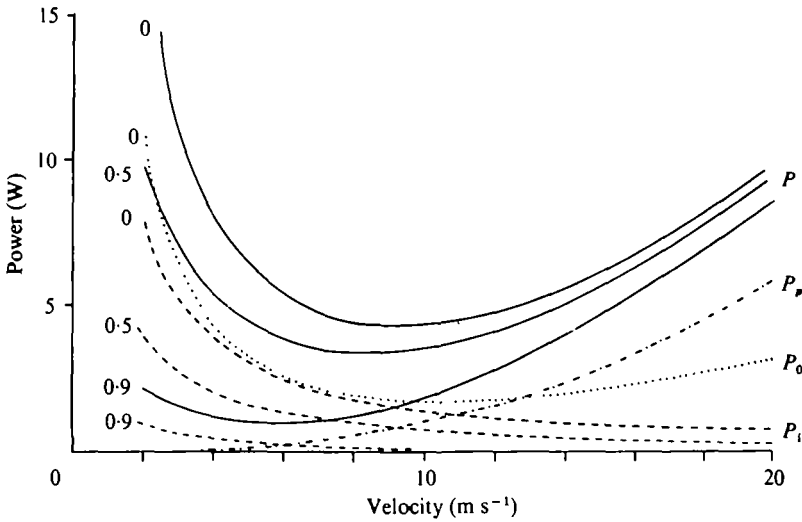


Fig. 4. Induced power (P_i), parasite power (P_p), profile power (P_0), and total power (P) required for forward, flapping flight by a black skimmer weighing 3.43 N at differing flight velocities. All are calculated with an interference coefficient of 0 (no ground effect), and P_i and P also shown for coefficients of 0.5 (bird is 7 cm above the water surface) and 0.9 (bird is 1 cm above the water).

through the wing disc, S_a , which is the area of a circle with diameter equal to the wing span, b (i.e. $S_a = \frac{1}{2}\pi b^2$). The induced drag of an aerofoil is $D_i = \frac{1}{2}L^2/\rho V^2 S_a k$, where L is lift (= body weight for horizontal flight), ρ is the air density (1.18 kg m^{-3}) V is the flight velocity (m s^{-1}) and k is the aerofoil efficiency factor. The value of k is about 0.7 for birds (Tucker, 1973; Greenwalt, 1975). The power required to overcome D_i is

$$P_i = VD_i = \frac{1}{2}L^2/\rho V S_a k.$$

Values of P_i were calculated after Tucker (1973) for a 3.43 N skimmer during horizontal forward flight at different velocities (Fig. 4).

Parasite drag (D_p) and parasite power (P_p) are calculated as

$$D_p = \frac{1}{2}\rho V^3 AC_{d,p},$$

$$P_p = \frac{1}{2}\rho V^3 AC_{d,p}.$$

where A is the projected area of the body and $C_{d,p}$ is the parasite drag coefficient, a dimensionless quantity which is independent of V and is a function only of the geometry of the body. Empirical data of Tucker (1973) allow the estimation of D_p and P_p for skimmers (Fig. 4).

Profile drag (D_0) and profile power (P_0) are the most difficult drag and power requirements to estimate. The D_0 and P_0 can be expressed as

$$D_0 = \frac{1}{2}\rho V^3 A' C_{d,0},$$

$$P_0 = \frac{1}{2}\rho V^3 A' C_{d,0},$$

where A' is the projected area of the wings and $C_{d,0}$ is the profile drag coefficient. However, empirical data for fixed-wing aircraft (Reid, 1932) and helicopters (Gessow

& Myers, 1952) indicate that $C_{d,0}$ is not independent of flight velocity. Pennycuik (1969, 1975) suggested that $C_{d,0}$ was proportional to V^{-3} and that P_0 was independent of V . Greenwalt (1975) assumed that $P_0 \propto V^{2.7}$, based upon the coefficient for skin friction. Tucker (1973, 1974) assumes that $P \propto V^{-0.5}(P_i + P_p)$. Though there is no theoretical basis to assume that P_0 is in any manner dependent upon P_i or P_p , Tucker's result was obtained as a best fit to empirical data for the metabolic cost of bird flight, and yields a relationship between P_0 and V which is similar to that for fixed-wing aircraft and helicopters. Fig. 4 presents estimates of P_0 for skimmers based upon the equations of Tucker (1973, 1974).

The sum of P_i , P_p and P_0 yields the total power requirement for horizontal forward flight, P (Figure 4). The actual power expenditure of the bird (P_r) would be about $5P$ because of the mechanical inefficiency of muscle contractions.

Skimming flight

In the transition from flapping to gliding flight, the aerodynamic power expenditure of the bird, P_r , is considerably reduced to about 1.5–2 times resting metabolism, or 3 W (Baudinette & Schmidt-Nielsen, 1974). There is, however, little change in the power required for horizontal, forward flight, and so the bird must continually decrease in altitude to overcome the drag forces with gravitational force. The glide angle (θ) and the sink velocity (V_s) are calculated as

$$\theta = 90 - \arctan (\text{lift/drag}),$$

$$V_s = V \tan \theta$$

(Pennycuik, 1972). The θ and V_s were calculated for skimmers flying at several velocities (Fig. 5).

GROUND EFFECT

The previous calculations for D_i (and parameters dependent upon D_i , i.e. P_i , P_0 , P , P_r , θ , V_s) are valid only if the aerofoil (wings) is at an infinite distance from a surface, such as the ground or water. Ground effect, the reduction in drag and increase in lift of aerofoils close to the ground, was recognized by early aerodynamicists (see Reid, 1932). A simple explanation for ground effect utilizes the method of images. An image aerofoil can be considered to be at a distance, z , below the ground without altering the actual flow streamlines of the real aerofoil, at a distance z above the ground. The image aerofoil will cause a reduction in the downwash angle, and hence D_i and P_i , of the real aerofoil. The extent to which ground effect reduces D_i is dependent upon the gap-span ratio, z/b . The equation for D_i , incorporating ground effect, is

$$D_i = \frac{1}{2} L^2 \cdot (1 - \sigma) / \rho V^2 S_a k,$$

where σ is an interference coefficient. The value of σ is negligible if $z > b$, but σ exponentially approaches 1 as z approaches 0. Values of σ as a function of z/b are tabulated in Reid (1932).

We have recalculated P_i , P , θ and V_s for skimmers with their wings 7 cm above the water ($\sigma = 0.5$) and 1 cm above the water ($\sigma = 0.9$), and these data are included in Figs. 4 and 5.

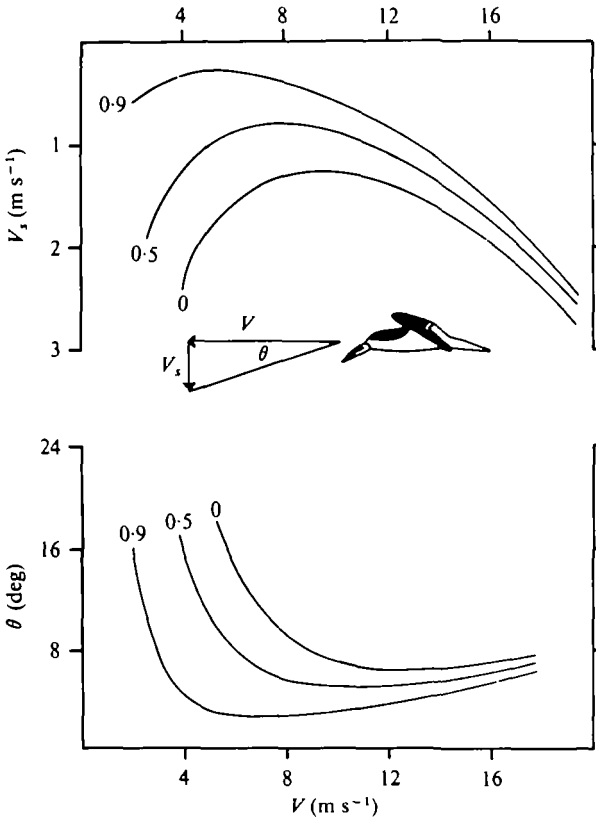


Fig. 5. Sink velocity (V_s) and glide angle (θ) of black skimmers at different forward velocities for interference coefficients of 0, 0.5 and 0.9.

HYDRODYNAMICS

The hydrodynamic drag force on the beak was measured with the beak submerged 3 cm in water flowing at 0.59 m s^{-1} at a number of angles of inclination. The total drag force was dependent upon the inclination angle, and was lowest when the beak was perpendicular to the water (Fig. 6). The drag force varied from $7.8 \times 10^{-5} \text{ N}$ to $1.5 \times 10^{-4} \text{ N}$.

Under the experimental conditions, and during skimming, the angle of attack of the lower rhamphotheca to the water flow is 0° , i.e. the chord of the rhamphotheca is parallel to the water flow. Hence, there is no lift generated by the beak (perpendicular to the surface of the rhamphotheca) and there is no induced drag. There is also no parasite drag as only the blade of the rhamphotheca is submerged in the water.

The profile drag coefficient of aerofoils includes both a pressure drag and a skin friction drag coefficient, but skin friction is normally negligible. We assume that the lower rhamphotheca has a pressure drag coefficient equivalent to that of a similarly shaped aerofoil, i.e. $C_{d, \text{pressure}} \cong 0.005$ (Dommasch *et al.* 1969). The drag coefficient for skin friction, assuming laminar flow, can be calculated as

$$C_{d,f} = 1.328/\sqrt{R_e}$$

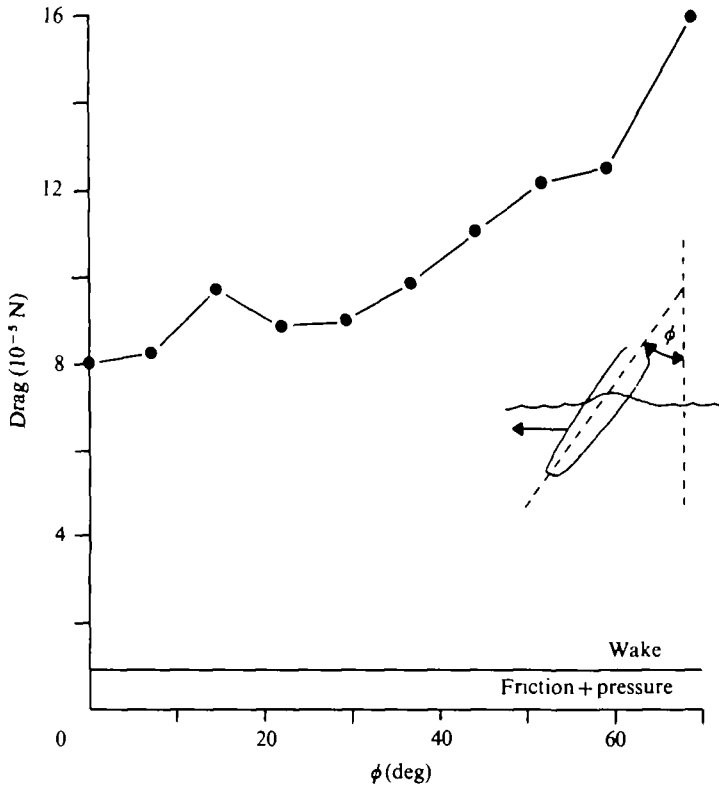


Fig. 6. Hydrodynamic drag force on the lower mandible submerged 3 cm in water flowing at 0.59 m s^{-1} . The approximate magnitude of wake drag and profile drag (pressure drag + friction drag) are indicated.

(Dommasch *et al.* 1969). The Reynolds number, R_e , is $V \cdot L/\nu$, where L is the characteristic length and ν is the kinematic viscosity of the medium; R_e under the experimental conditions was 4500 and $C_{d,f} = 0.02$ so that skin friction drag is about 1×10^{-6} N. Pressure drag is about 2.1×10^{-7} N.

Wake drag is an exceedingly complex force, being dependent upon the water depth, the form of the body, and the Froude number ($F_n = V/\sqrt{Lg}$, where g is the gravitational constant) (Dommasch *et al.* 1969; Lamb, 1945). Wake drag was calculated as total drag - (pressure + skin friction drag), and accounted for most of the drag force (Fig. 6).

To determine the hydrodynamic drag force acting upon the rhamphotheca at a normal flight velocity requires the scaling of the individual drag components with V . Pressure drag is proportional to V^2 (see aerodynamic section) and skin friction is proportional to $1/\sqrt{V}$. The manner in which wake drag scales with V is complex. Wake drag is maximal at velocities similar to the velocity of wave propagation along the water surface, and decreases at velocities lesser or greater than that of wave propagation. The experimental conditions maximized wake drag since the flow velocity (0.59 m s^{-1}) was close to the velocity of wave propagation (0.8 m s^{-1}).

The flight velocity of skimmers is more than 6 times the observed velocity of wave propagation (1.5 m s^{-1}) hence the wake drag is considerably less than the maximal value. Because drag is proportional to V^2 , the wake drag of a skimmer beak moving at 10 m s^{-1} at an angle of 45° to the surface is about $10^2/0.59^2$ times the measured drag. We estimate that the total drag on the beak at a velocity of 10 m s^{-1} is about $1 \times 10^{-4} \text{ N}$ (Table 2).

DISCUSSION

The aerodynamics of animal flight have been analysed using classical fixed-wing or helicopter aerodynamic theories (Pennycuik, 1969, 1972, 1975; Tucker, 1968, 1973, 1974; Greenwalt, 1975; compare with Prandtl & Tietjens, 1934; Reid, 1932; Dommasch *et al.* 1969; Gessow & Myers, 1952). However, such analyses are inadequate when there are interference effects, e.g. ground effect, formation flight. Formation flight and swimming in formation can result in a diminished cost of locomotion (Lissaman & Shollenberger, 1970; Weihs, 1974). The present study demonstrates the significance of ground effect to the flight energetics, foraging energetics and daily energy budget of the black skimmer (*Rhyncops nigra*).

The rhamphotheca of the lower mandible of *Rhyncops* is remarkably streamlined and has a low pressure drag coefficient. The drag incurred by moving the rhamphotheca through the water, the majority of which is due to wake drag, is negligible compared to the aerodynamic drag forces (Table 2).

The upper and lower rhamphothecae are covered with numerous small ridges, set at an angle of about 45° to the leading edge. Zusi (1962) suggested that these ridges facilitate the proprioceptive sensing of the position of the beak in the water. The height and orientation of the ridges is suggestive of aerodynamic baffles, which are used on the upper surface of aerofoils to hinder spanwise flow of the boundary layer, thereby retarding separation and minimising drag (Lignum, 1969). The ridges on the rhamphotheca may similarly retard separation of laminar flow over the beak rather than being proprioceptive sensors. The ridges would not significantly alter the drag characteristics of the beak as most of the drag is due to the formation of a wake, rather than pressure drag.

The kinematic analyses of flapping and skimming flight of *Rhyncops* presented in this study are similar to other reports for skimmers (Zusi, 1962) and other birds (Warner, 1931; Brown, 1951; Storer, 1945). The asymmetry of the wing stroke with respect to the horizontal plane through the body should diminish the potential adverse effect of flying close to the water on the stroke angle of the wings, particularly when the bird is attempting to increase altitude after skimming.

The aerodynamic forces associated with flapping flight and skimming are not readily amenable to empirical investigation, but were adequately predicted, for the purposes of the present study, from empirical and theoretical considerations. The total aerodynamic power requirement for horizontal flapping flight ($P = P_i + P_p + P_0$) of skimmers is lowest (4.4 W) at a velocity of 10 m s^{-1} , and increases at lower and higher velocity (Fig. 4). This predicted velocity for minimum power requirements (V_{mp}) is similar to the observed flight velocity (Zusi, 1962; present study).

During skimming, the power expenditure of the bird is probably about 1.5–2 times resting (Baudinette & Schmidt-Nielsen, 1974), or 3 W, which is much less than the expenditure of 22 W for flapping flight. However, the power requirements for flight

Table 2. Aerodynamic and hydrodynamic power expenditure of skimmer while feeding at a height of 7 cm above the water ($\sigma = 0.5$) at a velocity of 10 m s^{-1}

(See text for derivation of equations.)

	Aerodynamic (W)	Hydrodynamic (W)
Induced power, $P_i = \frac{1}{2}L^2(1-\sigma)/\rho VS_d k$	0.89	—
Parasite power $P_p = \frac{1}{2}\rho V^3 AC_{d,p}$	1.0	—
Profile power $P_0 = 2.1V^{-0.6}(P_i + P_p)$ or $P_0 = \frac{1}{2}\rho V^3 A' C_{d,0}$ $+ \frac{1}{2}\rho V^3 A' (1.328/\sqrt{R_d})$	1.8	—
Wake power P_w	—	10^{-3}
Total power $P = P_i + P_p + P_0 + P_w$	3.7	3×10^{-3}

are also diminished due to ground effect, so the bird has a smaller glide angle (θ) and sink velocity (V_s) than would be predicted (Fig. 5). Because the proportion of total power required for flight due to induced power increases at lower velocity, ground effect results in a greater percentage reduction in power requirements at lower V , though the absolute power requirement increases (Fig. 4). The height of the bird above the water determines the magnitude of the ground effect, and the distance of the wing tips above the water is probably more indicative of the reduction in induced drag than the height of the body since the interference coefficient, σ , increases exponentially with decreasing gap-span (Reid, 1932). The wing tips are often very close to the water during skimming, and occasionally touch the water surface.

The beneficial effect on the energetic cost of flight of being close to the water surface is apparent from the preceding theoretical considerations, but the manner in which ground effect influences the foraging efficiency and daily energy balance of skimmers is complex, as flight cost *per se* is only one of many factors influencing the energy balance.

Foraging efficiency (FE) is the rate at which energy is harvested (P_{har}) relative to the energetic cost of harvesting (P_{cost}), i.e. $\text{FE} = P_{\text{har}}/P_{\text{cost}}$. The harvest rate is (number of prey caught per unit time) \times (energy extracted from each prey item), or (number of prey caught per unit distance travelled) \times (distance travelled per unit time) \times (energy extracted per prey), i.e. $P_{\text{har}} = kVAE$, where k is an estimate of prey density and AE is the energy obtained per prey. If each prey weighed 0.05 N and the energy extracted was $2 \times 10^6 \text{ J N}^{-1}$, then $P_{\text{har}} = kV \times 10^5 \text{ W}$. The power expended during skimming is about $5 \times 4.4 \text{ W}$ in the absence of ground effect. Values of FE were calculated for skimmers over a range of flight velocities assuming different values of k , and the results are presented in Fig. 7 at different values of σ . Ground effect increases the foraging efficiency at any particular V , and the optimal V for skimming diminishes with increasing σ . Changing k alters the foraging efficiency but does not alter the optimal velocity. If a skimmer caught 1 prey every 6 min (e.g. Davis, 1951), then $k = 0.0002$ and foraging efficiency is between 11 ($\sigma = 0.5$) and 16 ($\sigma = 0.9$).

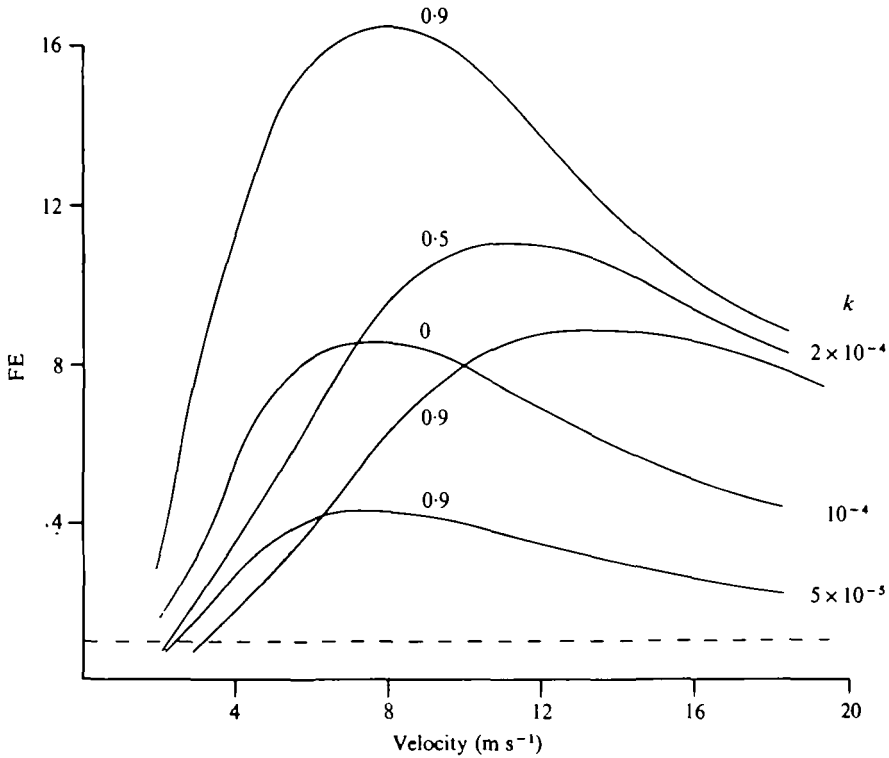


Fig. 7. Foraging efficiency (FE) of black skimmers for interference coefficients of 0, 0.5 and 0.9, and different prey densities ($k = 2 \times 10^{-4}$, 10^{-4} , 5×10^{-5}).

Though foraging efficiency is positive under almost all conditions, the daily energy budget of the skimmer is very sensitive to changes in k and σ because only a small portion of the day is spent foraging. If the skimmer spends h hours foraging per day, then the total energy harvested per day is hP_{har} . However, the total energy expended per day is about $[hP_{\text{cost}} + (24-h)P_{\text{mee}}]$, where P_{mee} is the mean energy expenditure for the non-harvesting period of the day. If we assume that P_{mee} is 3 times basal metabolic rate (King, 1974), then the daily energy balance (DEB) is $hP_{\text{har}}/[3(24-h)P_{\text{basal}} + hP_{\text{cost}}]$. Values of DEB were calculated for skimmers at different V and σ , with $k = 0.0002$ (Fig. 8). The foraging time (h) required to make DEB positive was 8, 6 and 4 hours if $\sigma = 0, 0.5$ and 0.9 respectively. Ground effect therefore enables a positive energy balance to be maintained with moderate foraging periods.

The predicted foraging times for a skimmer to remain in positive energy balance (about 6 h per day if $k = 0.0002$ and $\sigma = 0.5$) are realistic, although the assumptions required to determine FE and DEB were somewhat crude. We conclude that ground effect has a profound effect upon the foraging energetics and daily energy balance of skimmers. In the absence of ground effect, skimmers would spend considerably more time (> 8 h per day) foraging to achieve the positive energy balance required for growth and reproduction.

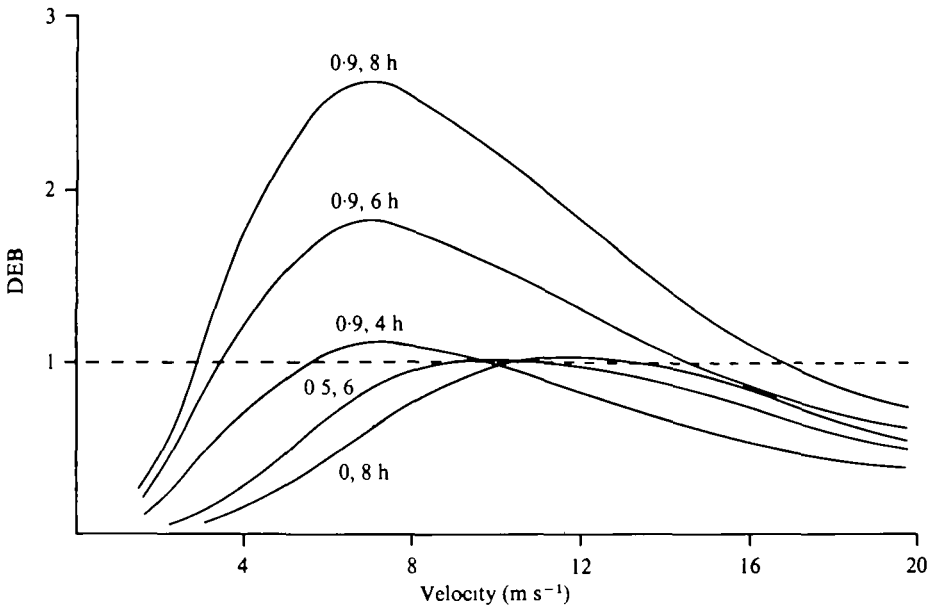


Fig. 8. Daily energy balance (DEB) of black skimmers for different interference coefficients (0, 0.5, 0.9) and different periods of foraging (4, 6, 8 h).

Ground effect is likely to be significant not only to skimmers, but also to many other birds, mammals and insects which fly close to a water or land surface. Large birds, such as vultures and albatross, may utilize ground effect to become airborne in view of their high wing loading, and ground effect may have been particularly important to the largest of flying vertebrates, the pterosaurs. Large birds, which would normally not be able to hover because of their high wing loading, are able to hover near the ground presumably because of ground effect (P. C. Withers, personal observations).

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