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## Scaling of Dynamic Soaring Flight in Procellariiformes Seabirds

ミズナギドリ目海鳥におけるダイナミックソアリングのスケーリング則

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### Introduction

Some of the large albatrosses, shearwaters, and petrels have an extreme travelling performance by covering large distances in their foraging trips and migration (Croxall et al., 2005; Jouventin and Wiemerskirch, 1990). The reason for this large distance and long time travelling performance is a unique flight mode termed dynamic soaring (Wilson, 1975). Using dynamic soaring, birds gain energy from the wind above the ocean surface to maintain flight. Wind speed is high far above the ocean but lower near the surface because of friction with the ocean surface and a wind gradient is made. Some studies examine the mechanism of how birds gain energy from the wind (Sachs et al., 2013; Pennycuick, 2002; Lissaman, 2005) and they all refer to the use of wind gradient. When dynamic soaring is observed in fine scale, it can be divided into 4 characteristic phases: upwind climb, turn to downwind, downwind glide, and turn to upwind (Fig. 1). The bird can fly sustainably by repeating this cycle. As a result, it is said that the bird is able to fly with less cost close to basal level when resting (Weimerskirch et al., 2000). Procellariiformes seabirds have long pointed wings with high aspect ratio which is suited for high speed gliding (Videler, 2006). Thus, dynamic soaring is fundamental for the extreme travelling performance of large Procellariiformes seabirds.

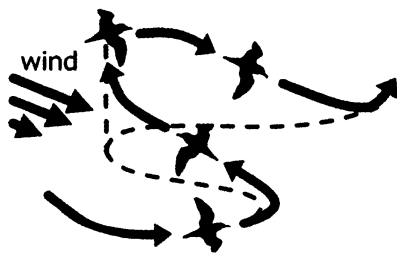


Fig. 1. Dynamic soaring

Dynamic soaring of large albatrosses, especially wandering albatross *Diomedea exulans*, attracted attention because of their energy efficient sustained flight almost without flapping, and most of the studies of dynamic soaring flight of seabirds investigate the flight of wandering albatross (Richardson, 2011; Sachs et al., 2013).

Some smaller species also perform dynamic soaring with some degrees of flapping included. Time percentage for flapping decreased with body size (Sato et al., 2009; Pennycuick, 1982), indicating that not all the energy for flight is gained from wind energy in small species. Therefore, it can be considered that there is an optimal flight style for each bird in response to their size and morphological character (Suryan et al., 2008). However, only few studies examine their flight performance in fine scale, due to the difficulty to observe their flight performance at open sea. Recent development of miniaturized animal borne data loggers enable fine scale and long duration recordings of bird movement

during flight. The aim of this study is to compare dynamic soaring flight of Procellariiformes species of different size.

## Experiments

We deployed acceleration logger (ORI-D3GT-5K: 8.4 g in air, 45 mm in length, 12 mm in diameter, Little Leonardo Ltd., Tokyo, Japan), video logger (18.2 g in air, 51 mm in length, 26 mm in width, and 19 mm in height), and GPS logger (15 g in air, TechnoSmArt, Guidonia Monteceilo, Italy) to streaked shearwaters *Calonectris leucomelas* to examine the movement during dynamic soaring. Acceleration logger recorded 3-axis acceleration (20 Hz), video logger recorded video data (30 frames per second), and GPS logger recorded bird position (1 Hz). Experiments were conducted at Funakoshi-Ohshima (39°24'N, 141°59'E), Japan. Power spectral density of acceleration was calculated by Fast Fourier Transformation (FFT) to discriminate behavioral movements of birds during flight. Two different peaks were seen in the PSDs. The higher peak of the frequency in PSDs is known to be the flapping frequency during cruising flight (Sato et al., 2009). We assumed that the lower peak of the frequency in PSDs might be related to the change of rolling angle of birds. To confirm this, change of rolling angle of the bird was followed using video data. As a result, value for the lower peak of PSDs was similar to the rolling cycle examined by video data. This supports that lower peak of the PSDs of the acceleration data represents the rolling movement of the bird. In addition, PSDs of acceleration data was calculated from 4 other Procellariiformes including white-chinned petrel *Procellaria aequinoctialis*, sooty albatross *Phoebetria fusca*, black-browed albatross *Thalassarche melanophrys*, and wandering albatross *Diomedea exulans* (Sato et al., 2009) and used for comparative study. GPS data was used to examine the correspondence of detail movements and flight paths of streaked shearwater. All analysis was done by Igor Pro (WaveMetrics, lake Oswego, OR, USA) and Ethographer (Sakamoto et al., 2009).

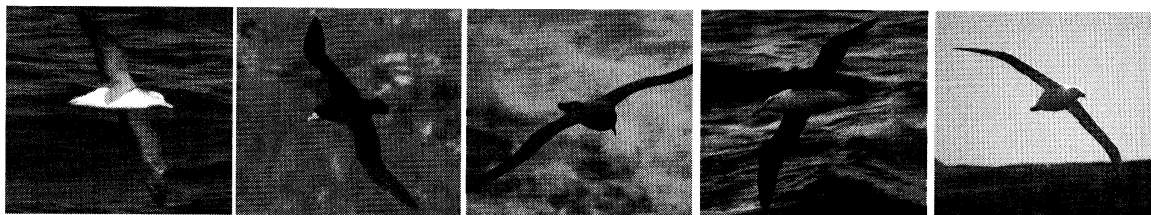


Fig. 2. Studied seabirds. Streaked shearwater, white-chinned petrel, sooty albatross, black-browed albatross, wandering albatross (from left to right).

## Results

### Scaling of cyclic rolling movement

Body mass of birds were  $569 \pm 51$  g (mean  $\pm$  s.d.) for streaked shearwater,  $1343 \pm 83$  g for white-chinned petrel,  $2240 \pm 10$  g for sooty albatrosses,  $3500 \pm 257$  g for black-browed albatrosses, and  $9600 \pm 1205$  g for wandering albatrosses. Rolling cycle of five species of

Procellariiformes detected by PSDs calculated from the acceleration data were  $2.5 \pm 0.5$  s (mean  $\pm$  s.d.) for streaked shearwaters,  $4.3 \pm 0.5$  s for white-chinned petrels,  $5.2 \pm 0.4$  s for sooty albatrosses,  $7.3 \pm 1.0$  s for black-browed albatrosses, and  $12.3 \pm 1.8$  s for wandering albatrosses. Rolling cycle of five species of Procellariiformes showed clear relationship with body mass, with rolling cycle being longer in larger species.

$$(\text{rolling cycle}) \propto (\text{body mass})^{0.57}$$

From the streaked shearwater with GPS and acceleration logger, 9 flights longer than 10 minutes were observed during 8 hours of recording. The flight track of streaked shearwater showed fine scale zigzag movement associated with dynamic soaring. The zigzag is consisted of slow speed phase which is assumed to be the windward climb and fast speed phase assumed to be the downwind descent. However, wind speed and wind direction were not recorded so speed represents the ground speed of the bird. Most of the flaps were observed when speed decreased where it is assumed to be the windward climb. Fewer flaps were seen during fast speed phase. The cyclic rolling movement started right after the turn from windward to downwind and ended at the bottom of downwind descent. This was also confirmed by video data.

## Discussion

From the GPS data, dynamic soaring cycle of streaked shearwaters and wandering albatrosses were around 8-10s and 10-15s, respectively. However, rolling cycle of streaked shearwaters and wandering albatrosses were 2.5s and 12.3s, respectively. Note that dynamic soaring cycle and rolling cycle were different. While dynamic soaring cycle represents the cyclic change of heading direction, rolling cycle represents the cyclic change of roll angle. Therefore, flapping, gliding, rolling, and other movements could be included in one dynamic soaring cycle. The rolling movement of large wandering albatross (12s) covered almost the entire dynamic soaring cycle (10-15s). This suggests that wandering albatrosses obtained energy from wind to sustain flight solely by rolling movement. On the other hand, the rolling movement of small streaked shearwaters did not cover the entire dynamic soaring cycle and could only be seen starting from the turn to downwind and through downwind glide. While the upwind climb, streaked shearwaters were flapping frequently and the body angle might be kept horizontal, so the rolling movement was not present. Thus, the rolling movement of streaked shearwaters was considerably shorter than the dynamic soaring cycle. These differences in flight styles might explain the scaling relationship of the rolling cycle in dynamic soaring seabirds.

We can consider that dynamic soaring is consisted of two phases: a phase where the bird gain energy from the wind and a phase where the bird itself produces energy by flapping.

In fact, from GPS and acceleration data, flight of streaked shearwater could be roughly divided into two phases: flapping phase during upwind climb and gliding during downwind descent. Rolling movement recorded in this study corresponded to the downwind descent phase where the bird gains energy from the wind. Dynamic soaring as a whole might be a combination of rolling, gliding, and flapping, however, when considering energy gain from the wind, rolling movement might have an essential role. Rolling cycle of five species of Procellariiformes showed clear relationship with body mass and there might be a definite explanation of this scaling relationship based on physical mechanism.

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