論文の内容の要旨

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論文題目

Ocean wind and flight behavior of soaring seabirds investigated using high resolution flight records

（海鳥の高解像度飛行データに基づく海上風推定および飛翔行動特性の解明）

Albatrosses and shearwaters are one of the animals that have superior locomotion ability that enables them to fly extensive ranges for a prolonged time. Wind has an inevitable effect on the movement of these seabirds because they are consistently exposed by wind by flying in the open ocean. Therefore, these seabirds should be able to react adequately to various wind conditions to save time and energy cost of traveling. Previous studies have reported that large-scale trans-oceanic migration of these seabirds is influenced by the large-scale global wind patterns. Besides large-scale wind patterns, seabirds also experience fine-scale changes of wind conditions. Behavioral adaptation to these fine-scale variations of wind are essential because these fine-scale adaptations scale up to shape the large-scale relationship between seabird’s movement and the environment. However, obtaining environmental variables are still difficult, especially at the same time and place where the free-ranging seabirds are moving, making it difficult to address these questions.

In this thesis, I focused on the relationship between wind and the flight of soaring seabirds. First, I evaluated a method to estimate the wind velocity from the bird’s trajectory itself obtained by bio-logging to solve the problem of the lack of fine-scale wind information. Then, the estimated winds were applied to describe the fine-scale flight behavior of flap-soaring shearwaters in relation to wind. To explain this flight behavior, numerical analysis was conducted to obtain flight characteristics of a theoretical seabird that minimize the cost of transport (CoT) in various wind conditions. Furthermore, the potential use of the estimated winds in meteorological aspect was discussed.

Wind estimation and verification using flight paths of seabirds soaring over the ocean surface

To estimate wind from seabird's flight, flight paths were obtained from three species of Procellariiformes seabirds; streaked shearwater (*Calonectris leucomelas*, *N*=13), Laysan albatross (*Phoebastria immutabilis*, *N*=2), and wandering albatross *(Diomedea exulans*, *N*=4), equipped with a GPS logger that recorded one positional fix per second. Flight paths of shearwaters and albatrosses showed tortuous patterns in the order of several tens of meters associated with a fluctuation of ground speed and direction. A condition was assumed that the fine-scale ground speed of soaring seabirds was predominantly affected by wind along the flight direction of the bird. In other words, ground speed increases in a tailwind, decreases in a headwind, and showed an intermediate value in a sidewind, according to the amount of assistance and resistance caused by the wind. Wind velocity was estimated by fitting a cosine curve to the relationship between ground speed and flight direction of the series of a 5-minutes section of flight; wind speed could be estimated as the one-half of the difference between the maximum and the minimum ground speed obtained from the fitted cosine curve, and wind direction could be estimated as the direction where the maximum ground speed was achieved.

To verify the accuracy of the estimated wind velocities, bird-based wind estimates were compared with satellite-based wind observations in 20 collocated points. It showed a significant correlation indicating that the estimated wind velocities were valid for further application in meteorology and behavioral ecology. However, wind speed was underestimated compared to the satellite-based observations possibly due to the altitude difference; satellites estimate wind at a 10 m reference height whereas shearwaters and albatrosses often fly in altitude of 2-8 m.

When the animal movements are significantly influenced by a physical environmental factor, those factors could be extracted by analyzing the animal movements which could be obtained by bio-logging. In this study, the tight relationship between the wind and the movements of soaring seabirds enabled to extract the wind information from a simple model of their movement.

Flap-soaring seabirds adjust flight patterns in response to wind

The superior ability of efficient flight in large Procellariiformes seabirds, such as albatrosses, is achieved by a flight strategy called dynamic soaring, which is a strategy to utilize the wind shear above the ocean to gain energy. Medium-sized Procellariiformes, such as shearwaters, are also known to perform dynamic soaring flight in combination with flapping which should be adjusted to various wind conditions in order to fly efficiently. However, the flap-soaring strategy in relation to wind of these medium-sized seabirds is poorly understood.

To investigate the fine-scale flight strategy of flap-soaring seabirds in relation to wind, GPS and acceleration loggers were simultaneously attached to 14 streaked shearwaters in September 2016. Total of 166.7 hours of flight data were divided into series of 5-minutes sections. Wind velocity and bird's air velocity was estimated from the bird's trajectory itself for each section by the method described in the previous section. Flapping ratio was determined from the body acceleration associated with flapping movement. As a result, streaked shearwaters experienced various bird-wind angle (e.g. headwind to tailwind) in weak winds, whereas preferred tail-sidewinds as wind speed increased. In addition, contrary to the general hypothesis that airspeed should decrease or kept nearly constant in tail-sidewinds, streaked shearwaters increased airspeed markedly in tailwinds. Although increasing airspeed requires more flight cost, these seabirds decreased flapping ratio in increasing tail-sidewind, resulting in a fast and low-cost flight.

To explain the observed flight characteristics of flap-soaring streaked shearwaters, an optimal control problem of a flap-soaring seabird was derived and solved by direct collocation method. Assuming that a theoretical bird could control its roll angle, lift coefficient (angle of attack), and flapping (thrust), the optimal control problem was solved to obtain the flight characteristics that minimize the CoT to travel in a defined direction in various wind conditions. As a result, the theoretical bird increased its airspeed in tail-sidewind. This was achieved by an increase of energy gain from the wind by dynamic soaring associated with a decrease in mechanical energy requirement. These results were consistent with the free-ranging birds which airspeed decreased in increasing tail-sidewind and at the same time flapping ratio decreased to near zero. This suggests that energy gain by dynamic soaring is essential to address the airspeed adjustment theory in flap-soaring seabirds. The difference in CoT between headwind and tailwind in theoretical birds was small in weak winds, however, it rapidly increased as the wind became stronger because a fast and low-cost flight was achieved in tailwind by dynamic soaring. Surprisingly, CoT increased also in a pure tailwind, so the minimum CoT was achieved in tail-sidewind. This was also consistent with the preference of tail-sidewind in free-ranging birds when the wind was strong.

Fine-scale records of flight data and the wind estimation method enabled to address the fine-scale adjustment of flight characteristics in relation to various wind conditions in a flap-soaring seabird, streaked shearwater. The flight characteristics, such as airspeed adjustment, flapping ratio, and preference of bird-wind angle of a theoretical shearwater to minimize the CoT was all qualitatively consistent with the flight characteristics recorded from a free-ranging streaked shearwater. This suggests that streaked shearwaters adjust their fine-scale flight behavior in relation to various wind conditions in order to minimize their COT during their foraging trips.

Conclusion

I evaluated a method to derive wind velocity experienced by the bird from the bird's trajectory itself. In a context of bird's flight behavior, the change in airspeed, flapping ratio, and bird-wind angle in relation to wind of a flap-soaring seabird was investigated using the estimated fine-scale wind information. To explain these flight behavior, a numerical analysis was conducted to simulate an optimal flight strategy of a flap-soaring bird to minimize the CoT in various wind conditions, in which the results agreed with the flight characteristics of the free-ranging birds. This study is the first to interpret these adjustments of flight behavior in flap-soaring seabirds as a strategy to minimize the CoT by effectively combining flapping and dynamic soaring in various wind conditions.

Extensive travel distances and prolonged flight durations of soaring seabirds enabled wide range estimation of wind velocity in fine-scale resolution (5 minutes, 2-5 km). In a meteorological context, these fine-scale bird-based wind estimates covered spatial gaps between the remote sensing measurements, such as in coastal areas where satellite-based wind measurements are obscured by the interference of land. In addition, the high temporal resolution of the bird-based winds detected the dynamic change in wind speed and direction in the Sanriku coast of North-East Japan, which could not be detected by the satellite-based wind observations two times per day. This suggests the possibility of further application of seabirds as a 'living ocean buoy' that could complement conventional wind observation methods.