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研究課題名（和文）Modeling the Habitat Suitability of Adelie penguins across Antarctica

研究課題名（英文）Modeling the Habitat Suitability of Adelie penguins across Antarctica

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研究成果の概要（和文）：本研究は環境変動下における南極のペンギン類の一年を通じた生態的ニッチを明らかにする目的で実施した。国際共同研究によりバイオロギング手法によるペンギンの行動追跡を複数地点で実施した。その結果、まず一年を通じたアデリーペンギンの渡り行動・潜水行動の記録を得て、海氷密接度、日長時間などの環境要因が行動の季節変化に強く影響することを明らかにした。次に、アデリーペンギンがクラゲを食べるという新しい行動を発見し、この行動が南半球に生息する4種7集団のペンギンで見られることを報告した。これらはペンギンの生態的ニッチの可変性に関する新規性の高い知見で、ペンギンの環境変動への応答を予測する上で重要である。

研究成果の概要（英文）：This project explored the year-round ecological niche of penguins in Antarctica, where environmental changes affect the food webs. Thanks to the bio-logging approach (data loggers deployed on animals) and to the setting up of an international network of experts in penguins’ ecology, the following progresses were achieved. First, the year-round migration and diving activity of Adelie penguins was revealed, showing the influence of the environment across seasons on their behaviour. Sea-ice concentration, but also daylight duration and probable deepening of prey were major drivers of these seasonal changes. Second, we discovered a new behaviour in Adelie penguins: the predation on jellyfish. From this discovery, another comparison was made at the scale of the southern hemisphere across seven penguin populations from four species, and confirmed this behaviour. This may change our perception of the penguins’ niche flexibility, and hence their expected response to environmental changes.

研究分野：Ecology

キーワード：Antarctica　Environmental changes　Modeling　Penguin　Spatial distribution　Food web

１．研究開始当初の背景

The Earth's climate is currently changing at an unprecedented pace. These changes include warming that originates mainly from carbon dioxide emissions, and the vast majority of this atmospheric carbon dioxide is stored in the oceans, the main carbon sink of the planet [1]. It is thus expected that marine life, and the marine food webs, are the most strongly impacted ones by global changes. Yet, the oceans' life and its response to these changes is comparatively the least studied [2].

Marine primary producers can nevertheless be monitored from satellites, at the oceans' surface. But the upper predators, more mobile, are challenging to survey, and for this reason it is still poorly understood how changes in the environment may affect the ability of predators to find food and ensure population persistence.

Today, bio-logging techniques (data loggers deployed on animals) provides a unique approach to study predators in the wild [3]. Studying predators may hence now provide a perspective on the oceans' food web functioning, as these predators (their activity, behavior, distribution or numbers) totally depend on the first levels of the food chain. Hence, any major change in the environment will be detectable from the predators. This recent approach to the oceans' functioning through predators (the "top-down" approach) is becoming widely used thanks to the development of small bio-logging devices.

The Antarctic is one of the most rapidly warming regions in the world, with structural and functional changes observable or expected in the ecosystem. In the West, the Antarctic Peninsula is experiencing dramatic warming (Fig 1). In the East, negative feedbacks of the warming leads to prolonged sea-ice in summer [4]. These changes may affect the development of the food chain, and ultimately, the predators.
The Adelie penguin is a key predator in this marine ecosystem. It is an abundant, widely distributed species and tightly associated to sea-ice to forage on marine prey. Adelie penguin populations exhibit contrasted trends across Antarctica, with those in the West now collapsing or even disappearing, while eastern populations are more stable or increasing [5].

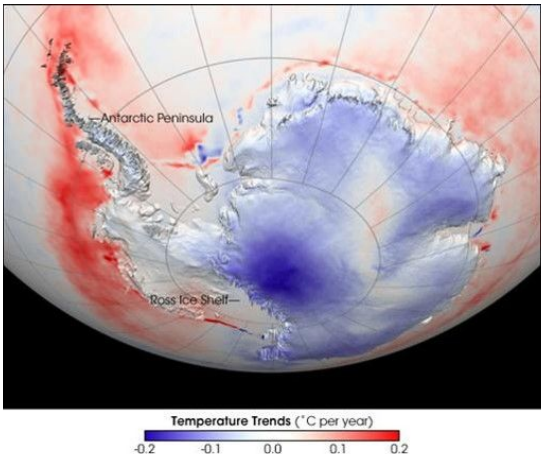

Figure 1: Satellite infrared imaging from NASA, temperature trend for 1982-2004.

Habitat modelling studies have showed that habitat quality during the summer chick-rearing period has changed for Adelie penguins over the recent past, and that these changes are contrasted regionally [6]. However, recent advances in techniques and concepts suggest that all periods of the species' life-cycle should be studied in order to understand key elements driving the species' demography [7].
Antarctica experiences extreme seasonality, and Adelie penguins must, after their breeding season in summer, face and survive the harsh Antarctic winter, during which prey is less accessible and penguins are continuously at sea.

２．研究の目的

The aims of this research were to reveal the ecological mechanisms by which Adelie penguins may be affected by changes in the environment. We used modern tools (bio-logging, statistical modelling) to explore the links between the penguins' exploited habitat and its environmental characteristics. From these links, our goal was to provide the basis to predict how the penguin populations may be impacted by changes in the near future. More generally, if successful, we intended to make this step-by-step approach applicable to other ecosystems threatened by climate changes.

３．研究の方法

3.1 Light-based geolocation loggers: these devices are much smaller than satellite transmitters or GPS loggers, which makes them usable on wild animals for prolonged surveys in the wild [e.g., 8]. The light-based geolocation loggers simply record the ambient light levels along time. Upon recovery of the logger, this light signal allows to calculate the sunrise and sunset times, and based on the reference time value, to estimate the past daily location of the animal. In this survey, we used state-of-the-art loggers (Lotek LAT2500: 3.6 g), which also record ambient pressure (hence dive depth) every two minutes, in addition to the daily location, year-round. This allowed us to reveal for the first time the diving activity of the penguins outside their breeding period.

<u>3.2 Video data loggers:</u> over the last few years, video data loggers have demonstrated their potential to bring unique information on the wild animals' behavior [9]. Video can indeed show unequivocally interactions with prey, with conspecific individuals or with other species. Therefore, it now becomes possible outside from the lab to quantify prey abundance, accessibility, handling time by the diving predator or even concurrence among predators, and to directly identify prey items, thanks to the use of these video loggers. However, their recording time and battery duration are still limited to a few hours, restricting their use in this project to the short at-sea foraging trips performed by the penguins during their chick-rearing period only. In this project, we used video-loggers from Little Leonardo (Tokyo), models DVL200 (15 g, 2.5 h recording capacity) and DVL200 M (22 g, 4 h recording capacity; Fig 2).

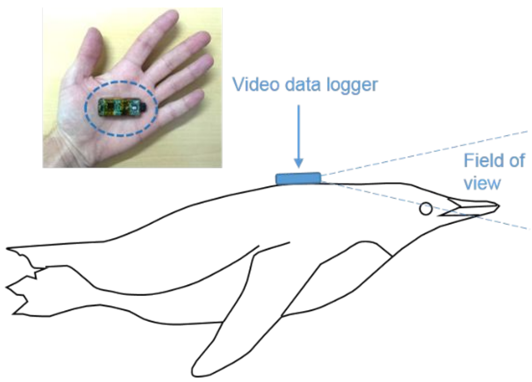

Figure 2: Video loggers used in this study, relative size and position on the animal

<u>3.3 Multi-site approach:</u> wild populations may be scattered across the distribution range of the species. Hence, all individuals in a given species do not experience the same environmental conditions at a given time. In Antarctica, the climatic trends are contrasted between regions: in order to statistically capture the full range of ecological response of the predators facing a wide array of climatic changes, and hence to understand divergent demographic patterns, one of the goals of this project was to gather data from several (and if possible, contrasted) regions (Fig 3).

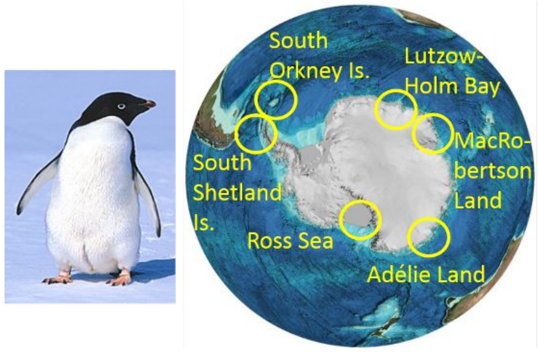

Figure 3: Antarctic Adelie penguin colonies where collaboration was achieved or launched in the frame of this project.

<u>3.4 Habitat modelling:</u> statistical modelling may reveal the link with the environment that gives to the bio-logging data their full ecological potential. In this project, one objective was to study the link between environmental structures and the habitat suitability for penguins. We used the Mahalanobis Distance Factorial Analysis (MADIFA [10]; Fig 4).

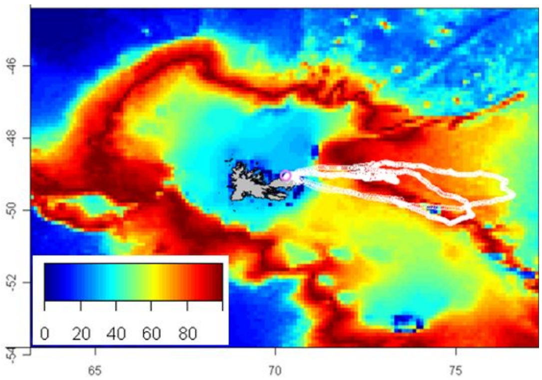

Figure 4: example of % habitat suitability mapping using MADIFA. The penguin tracks (in white) directed towards the shelf slope around the island, which was highlighted as the main targeted structure for the whole population [Thiebot et al.].

In this approach, the penguin daily locations are overlaid on environmental data for the corresponding period. From this step, we derive an optimal niche for the penguins, corresponding to a range of favored conditions [8]. This quantified niche allows to (1) explore the full habitat space, beyond the points where surveyed individuals were located; (2) compare the habitat exploited by distant populations, and (3) allows to predict where will be found the optimal habitat of penguins in the future, under a given scenario of the environmental variables' changes.

４．研究成果

4.1 Year-round ecology of penguins:

In this project we were able to gather data on Adelie penguins from the UK (South Orkney Is.), from USA (South Shetland Is.), from France (Adelie Land), and from Japan (Lutzow-Holm Bay). During the course of the project, we newly collected one dataset (from Adelie Land, 2015). Success of recovery was higher than the expected 70%: we recovered 13 of the 15 deployed loggers (87%), though one logger's data still need to be retrieved by the manufacturer.
Data showed that penguins migrated in general to the northernmost edge of the sea-ice cover. This led the penguins to move northward for most of the sites (Fig 5), but southward for the birds from the northernmost site (Signy, South Orkney Is.). This result demonstrates that the Adelie penguin is an adequate eco-indicating species for Antarctic sea-ice. However, there were significant differences between sites, with penguins from Syowa (Lutzow-Holm Bay) experiencing consistently heavier sea-ice conditions than their neighbours at Dumont d'Urville (Adelie Land; Fig 5).

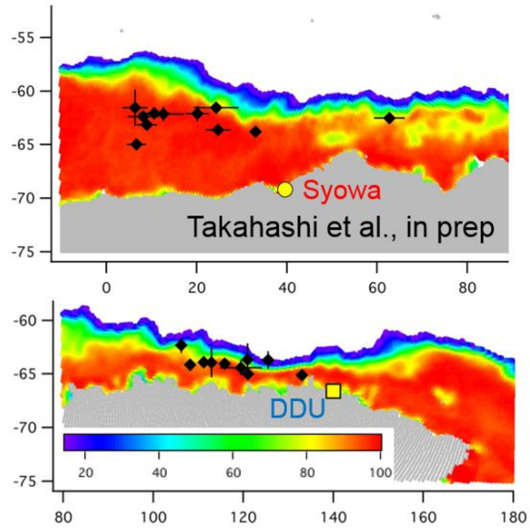

Figure 5: map of the average penguins' location in July (black dots) for the Japanese Syowa base (up), and the French Dumont-d'Urville base (down). Colors in the background show the corresponding sea-ice concentration.

Datasets are still to gather from USA (Ross Sea, existing dataset), and Australia (MacRobertson Land, to be collected). For this reason, habitat modelling results are still to be finalized using the full dataset from all sites.
On the other, hand, we obtained here the first data on diving activity of Adelie penguins across seasons: these are available from two sites, and for two years at one site (Fig 6). These data clearly show that penguins increase their diving effort before molt (when the penguins renew their feathers and cannot dive), after the molt (when they need to recover from the long fast endured during molting), and when preparing the next breeding season (which starts in November), when they need to store energy reserves. This result shows that minimal daylight in winter seems to limit daily foraging activity of the penguins: in this perspective, it explains why penguins would migrate to the north, regardless of sea-ice conditions. Indeed, this movement seems related to the need for penguins to hunt for food, with sufficient daylight duration.

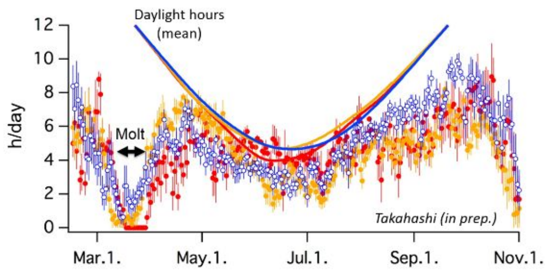

Figure 6: Average time spent diving per day for the Adelie penguins surveyed from Syowa in 2011 (red), in 2012 (orange), and from Dumont d'Urville in 2015 (blue), across seasons. The curves indicate the available daylight hours at the penguins' location.

Two papers are close to be submitted, about the Adelie penguins' year-round activity and link with seasonal sea-ice; and another one will be written with habitat modelling results from all sites. The latter will notably aim at anticipating how the different Adelie penguin populations may be impacted by current changes in sea-ice conditions (increasing or decreasing distance to the optimal habitat).

4.2 Preying on jellyfish: a new behavior?

In 2014-2015 breeding season, video loggers deployed on penguins at Dumont d'Urville newly revealed predation on jellyfish (published in Marine Biology, with high media coverage). Environmental conditions were very unusual that year (persisting sea-ice during summer), causing a bad breeding success for penguins. It was thus intriguing whether penguins were then compensating for the lack of usual prey in these conditions, by targeting such unusual prey, assumed to be very poor in energy. Statistical analyses showed that penguins were more likely to eat jellyfish when these had prominent gonads, where energy is 5 times denser. Jellyfishes' gonads could thus support endothermic predators as food (Fig 7).

Figure 7: A jellyfish with prominent gonad about to be captured by an Adelie penguin in eastern Antarctica, in January 2015 (screen shot from footage).

We developed another network of penguin ecologists working with video loggers (from 5 countries: Japan, France, Australia, Argentina, New Zealand) to test this hypothesis more widely in the southern oceans. This work is accepted in Frontiers in Ecology and the Environment (impact factor 8.5). Our paper shows that penguins (106 studied individuals from 4 species, 7 populations) currently prey on jellyfish, and still can find their regular prey in the oceans. It hence appears likely that this behavior is not related to a change of prey availability, but is newly observed thanks to the video loggers. This work hence provides a new perspective on the marine food web structure, with jellyfishes playing a more significant role in energy transfers, than initially expected. Further video monitoring of penguins is highly desirable in the western Antarctic to test whether salps (gelatinous herbivores) may also be eaten by penguins, as salps are assumed to increase massively there at the expense of krill (penguins' main prey) because of environmental changes.

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５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　2　件）

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〔その他〕
ホームページ等
https://sites.google.com/site/jbthiebot/publications

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