

1 Supplementary Methods

Our sea ice-dependent-metapopulation model projects the population vector \mathbf{n} —comprising the population size n_i in each colony i —from time t to $t + 1$ using:

$$\mathbf{n}(t + 1) = \mathbf{D}[\mathbf{x}(t), \mathbf{n}(t)] \mathbf{F}[\mathbf{x}(t), \mathbf{n}(t)] \mathbf{n}(t) \quad (1)$$

to indicate that the projection interval is divided into two main phases of possibly different duration: the reproduction phase (\mathbf{F}) followed by the dispersal phase (\mathbf{D})¹. The reproduction matrix \mathbf{F} is constructed using the Ricker model², which includes the intrinsic population growth rate $r_i(t)$, which vary in time, and the carrying capacity of the colony, K_i , which is set to be constant over the entire time period. The dispersal phase (\mathbf{D}) combines various dispersal behaviors and dispersal events. The projection matrices \mathbf{D} and \mathbf{F} depend on both the current the population size $\mathbf{n}(t)$ and the habitat characteristics (including sea ice concentrations anomalies), $\mathbf{x}(t)$, that vary among colonies and over time, t . The global population size at time t is given by $N_t = \sum_i n_i(t)$.

1.1 Reproduction phase

The reproduction matrix, \mathbf{F} , is constructed using the Ricker model including the intrinsic growth rate of each colony $r_i(t)$ and the carrying capacity of each colony K_i . Negative density-dependence effects occur within crowded favorable habitats ($r_i > 0$ and $n_i > K_i$) while populations tend to go extinct within poor habitat colonies ($r_i \leq 0$). Our understanding of density dependence processes is extremely limited for emperor penguins (see discussion in Appendix S1 of Jenouvrier et al. 2012). Density dependence may occur at breeding ground due to competition for space. For example, the Beaufort Island colony growth is limited by the limited space available on the fast ice plate next to the island (Kooyman et al. 2007). Competition for resources may also occur, although emperor penguins are able to forage over long distances over wide areas, probably reducing intra-specific competition impact.

The intrinsic growth rate For each projection interval t , the intrinsic growth rate of each colony $r_i(t)$ is projected by a nonlinear, stochastic, sea-ice dependent, two-sex, stage-classified matrix $\mathbf{A}[\theta[\mathbf{x}(t), \mathbf{n}(t)]]$, including the demographic rates (reproduction and survival) $\theta[\mathbf{x}(t), \mathbf{n}(t)]$ (described in more detail in Jenouvrier et al. 2010, 2012). $\mathbf{A}[\theta[\mathbf{x}(t), \mathbf{n}(t)]]$ includes a sequence of seasonal behaviours (arrival to the colony, mating, breeding) and accounts for differences in adult survival between males and females as

¹Note on notation: In this paper, matrices are denoted by upper case bold symbols (e.g. \mathbf{F}) and vectors by lower case bold symbols (\mathbf{n}); f_{ij} is the (i, j) entry of the matrix \mathbf{F} , n_i is the i th entry of the vector \mathbf{n} .

²Ricker, W. E. (1954) Stock and Recruitment Journal of the Fisheries Research Board of Canada, 11(5): 559–623.

function of sea ice concentration anomalies $\mathbf{x}(t)$. $\mathbf{A}[\theta[\mathbf{x}(t), \mathbf{n}(t)]]$ depends on $\mathbf{n}(t)$ because the reproduction is function of the proportion of males and females within the population through mating processes (Jenouvrier et al. 2010).

The matrix $\mathbf{A}[\theta[\mathbf{x}(t), \mathbf{n}(t)]]$ includes 5 stages: male and female pre-breeders (birds that have yet to breed for the first time), breeding pairs, and male and female non-breeders (birds that have bred before but do not do so in the current year). The demographic rates $\theta[\mathbf{x}(t), \mathbf{n}(t)]$ describing the transitions between these stages from year t to $t+1$ includes the probability that an individual of a given stage returns to the breeding site, the probability of mating as a function of the availability of potential mates, the probability of breeding success (raising an offspring given that the female lays an egg), the primary sex ratio (fixed at 0.5), the survival of offspring during the first year at sea, and the annual survival of pre-breeders, non-breeders and male and female breeders.

The functional relationships between demographic parameters and sea ice concentration anomalies depend on four seasons (described in detail in Jenouvrier et al. 2012):

1. The non-breeding season from January to March,
2. The arrival, copulation and laying period (April–May), hereafter called the laying period,
3. The incubation period (June–July),
4. The rearing period (August–December).

For example, relationships can be sigmoid functions, with quadratic functional relationship between demographic rate and sea ice:

$$\theta_i(\mathbf{x}(t)) = g(y = \beta_0 + \beta_1\mathbf{x}(t) + \beta_2\mathbf{x}(t)^2 + \epsilon_t) \quad (2)$$

including the parameter estimates β_k and the environmental stochasticity ϵ generated by other unknown variables. ϵ is a stochastic environmental noise of mean 0, and variance $\text{var}(\epsilon_t)$ and is considered as an additional variability independent from sea ice. g is the inverse logit link function so that $\theta_i \in [0 \ 1]$.

In addition, we added here extreme events that affect the reproduction and survival of emperor penguins by using two environmental states: extreme and ordinary. Each environmental state is associated with a set of population matrices based on the occurrence of extreme events: $\mathbf{A}_{EX} = [\mathbf{A}_1, \dots, \mathbf{A}_{ne}]$, with ne the number of extreme years, and \mathbf{A}_{ORD} includes all other years. At each time step, a matrix was selected randomly within a specific set of matrices according to the frequency of extreme events f to project the population between time t and $t + 1$, hence calculating the intrinsic growth rate of each colony $r_i(t)$.

The carrying capacity For emperor penguins, estimating the carrying capacity of the environment is a daunting task because population time-series are limited to a few colonies around Antarctica, and no study thus far has reported the resources and breeding habitat availability. Using the population projections from the stochastic sea-ice dependent model that excludes density dependence (Jenouvrier et al. 2014, 2017), Jenouvrier et al. (2017) estimated the carrying capacity of each colony as $K_i = 2N_0$, with N_0 the initial size of the population observed in 2009 (Jenouvrier et al. 2014, Fretwell et al. 2009).

1.2 The dispersal phase.

Finally, the model includes inter-colony movements. A dispersal event includes the three stages: (1) emigration from the resident colony, (2) search for new colony among other colonies with an average dispersal distance d (transfer), and (3) settlement in a new colony. The duration of the transfer phase can vary, as the final settlement in a new colony may occur after several events (e.g., an individual may not settle in its first choice habitat if that habitat has reached its carrying capacity $n_i \geq K_i$).

In our model, movements of individuals among colonies are divided into two successive dispersal events to account for a time-limited search. Indeed for emperor penguins the breeding season lasts 9 months, and thus the timing for prospecting other colonies during the non-breeding season is limited. During the first dispersal event (\mathbf{D}^1) individuals may select the habitat with highest quality (informed search) or settle in a random habitat. During the second dispersal event (\mathbf{D}^2) individuals that reached a saturated colony leave and settle randomly in a new colony (see Fig. 1 in Jenouvrier et al. 2017). The later is a way to account for a dispersal cost of gathering information for the informed search (see discussion in Jenouvrier et al. 2017). For emperor penguins, the emigration rates and the dispersal distance can not be quantified, hence we developed several scenarios relevant for the biology of the species (see Jenouvrier et al. 2017 for more details).

The dispersal projection matrix \mathbf{D} is thus

$$\mathbf{D} := \mathbf{D}^2 \mathbf{D}^1. \quad (3)$$

and each dispersal matrix \mathbf{D}^e is written

$$\mathbf{D}^e := \mathbf{S}^e[\mathbf{x}] \mathbf{M}^e[\mathbf{x}, \mathbf{n}_e] \quad (4)$$

to indicate that matrices for searching behavior, \mathbf{S}^e , and emigration, \mathbf{M}^e , depend on the population size at the start of the event (n_e) as well as the environmental conditions $\mathbf{x}(t)$.

The first dispersal event The emigration rate for each colony i depends on the overall quality of the habitat, which is measured by the median of the realized population growth \bar{r}_i^* . The emigration rate increases linearly from $m^1 = 0$ at $\bar{r} \geq 0$ to $m^1 = 1$ at critical

value $\overline{r_c^*} < 0$. The emigration matrix thus only depends on the ratio $\overline{\mathbf{r}^*(t)}/\overline{r_c^*}$,

$$\mathbf{M}^1 := \mathbf{M}^1 \left[\frac{\overline{\mathbf{r}^*(t)}}{\overline{r_c^*}} \right]. \quad (5)$$

A critical threshold $\overline{r_c^*}$ close to 0, corresponds to high dispersion scenario while a larger negative threshold reflects low dispersion.

Once individuals have left their colonies, we assume that they search for a new colony using two different behaviors: an informed searching behavior (\mathbf{S}_I) and a random searching behavior (\mathbf{S}_R).

The random search assumes that dispersers randomly seek a colony within the limits of the maximum dispersal distance. Thus the probability of selecting a colony depends on the mean dispersal distance of the emperor penguin, d , and the matrix of distance between colonies ($\text{dist}(i, j)$) included in the vector of habitat descriptors \mathbf{x} .

$$\mathbf{S}_R := \mathbf{S}_R[\mathbf{x}, d]. \quad (6)$$

The matrix $\text{dist}(i, j)$ corresponds to the coastal distance between colonies i and j derived from the location of know emperor penguin colonies.

Conversely, *the informed search* assumes that dispersers search for the most favorable habitat they can reach; we use $\overline{\mathbf{r}^*}$ as a descriptor of the quality of the habitat. Thus the informed search matrix is also a function of $\overline{r^*}$:

$$\mathbf{S}_I := \mathbf{S}_I[\overline{\mathbf{r}^*(t)}, \mathbf{X}, d]. \quad (7)$$

If the selected colony is not at carrying capacity, individuals settle in this new habitat. However, individuals are not able to settle in colonies that have reached their carrying capacities after the first dispersal event, and will conduct a novel search during the second dispersal event.

During the second dispersal event, the surplus individuals leave and randomly settle in another colony regardless of their dispersal strategy in their first event. Thus the emigration matrices depend on the carrying capacity \mathbf{K} , the population vector \mathbf{n} at the end of the first dispersal event, and a random search matrix:

$$\mathbf{M}^2 := \mathbf{M}^2[\mathbf{K}, \mathbf{n}] \quad \text{and} \quad \mathbf{S}^2 := \mathbf{S}_R. \quad (8)$$

Note that because of our random settlement assumption during this second dispersal event, individuals may come back to their resident colony if they first reached an over-crowded colony.