

The following supplements accompany the article

Large-scale climate and local weather drive interannual variability in Adélie penguin chick fledging mass

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SUPPLEMENT 1. Additional tables

Table S1. The number of days with specific weather conditions were determined during the chick-rearing period according to the following criteria. The minimum/maximum air temperature refers to the minimum/maximum recorded on each day

| Weather condition | Threshold | Reference/Justification |
|----------------------|--|---|
| High wind | mean $> 6 \text{ m s}^{-1}$ | Chapman et al. (2011) |
| Cold air temperature | minimum $< 0^{\circ}\text{C}$ | Chapman et al. (2011) |
| High air temperature | maximum $> 7^{\circ}\text{C}$ | Chappell et al. (1990) |
| Chill factor | minimum temp. $< 0^{\circ}\text{C}$ & mean wind speed $> 4 \text{ m s}^{-1}$ | Chapman et al. (2011); $> 4 \text{ m s}^{-1}$ is a moderately high wind speed |
| Heat stress | maximum temp. $> 7^{\circ}\text{C}$ & mean wind $< 1.5 \text{ m s}^{-1}$ | Chappell et al. (1990); $< 1.5 \text{ m s}^{-1}$ is a low wind speed |
| No precipitation | precipitation = 0 cm | Assumed any precipitation could negatively impact chicks |

Table S2. Variable transformations to remove significant trends over time or to achieve normality

| Variable | Transformation | Justification |
|------------------------------|----------------------------|-------------------------------|
| Air temperature | Detrended; log transformed | Negative linear trend; skewed |
| Mean wind chill | Detrended | Negative linear trend |
| <i>u</i> wind component | Detrended | Positive linear trend |
| Days with zero precipitation | Detrended | Positive linear trend |
| <i>v</i> wind component | Square root transformed | Skewed |
| Solid precipitation | Square root transformed | Skewed |
| High wind | Square root transformed | Skewed |
| Chill factor | Log transformed | Skewed |
| Cold temperature | Log transformed | Skewed |
| CRH suitability | Log transformed | Skewed |

SUPPLEMENT 2. Additional figures.

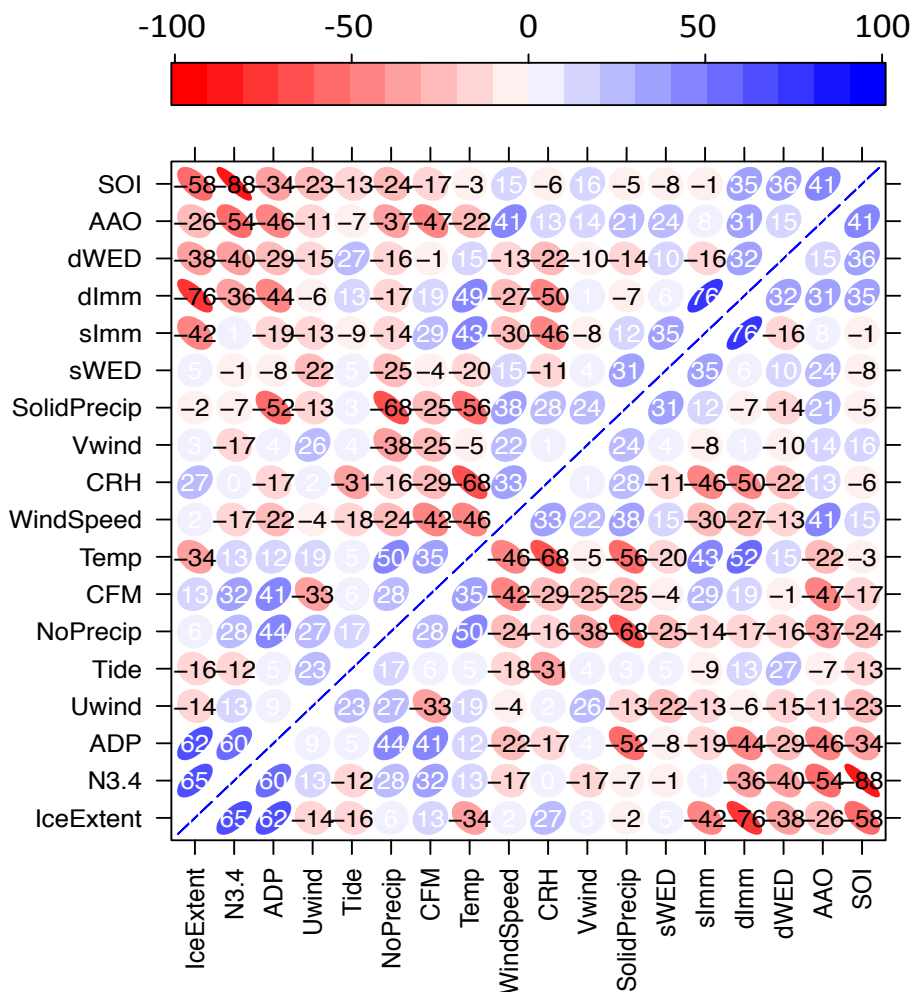


Fig. S1. Correlogram showing correlation coefficients using Spearman's rank correlation ρ , from 1989 to 2011. For legibility, the values range from -100 to 100 but can be interpreted as Spearman's rank correlation ρ , which ranges from -1 to 1 . Each correlation is displayed by color and intensity of shading, where warm colors indicate a negative correlation, and cool colors indicate a positive relationship. The variables in the correlogram are chick fledging mass (CFM), Antarctic Oscillation (AAO), El Niño 3.4 (N3.4), Antarctic Dipole (ADP), Southern Oscillation Index (SOI), chick-rearing habitat suitability (CRH), air temperature (Temp), u wind component (Uwind), v wind component (Vwind), wind speed (WindSpeed), solid precipitation (SolidPrecip), number of days without precipitation (NoPrecip), seasonal fraction of diurnal tides (Tide), sea ice extent (IceExtent), krill wet-mass energy density (WED) from the dynamic (dWED) and static scenario (sWED), and the proportion of immature krill in the dynamic (dImm) and static scenario (sImm). Days with high winds, cold temperatures, high temperatures, heat stress, chill factor, and mean wind chill were not included in the figure because they were collinear, and mean air temperature and mean wind speed had a higher correlation to CFM. Sea ice duration and retreat day were also not included because they are collinear with sea ice extent. Temp, NoPrecip, and Uwind were detrended.

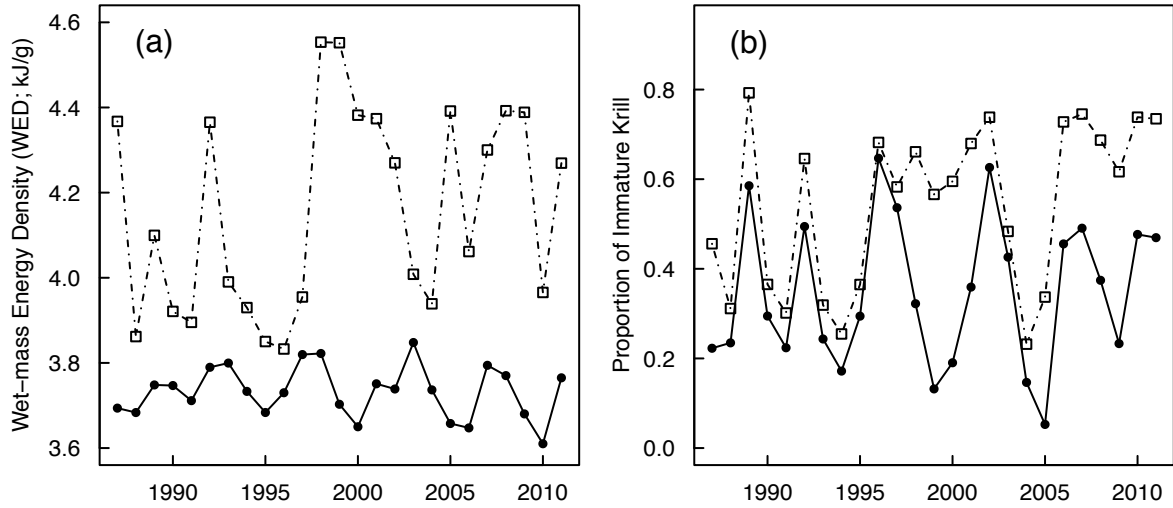


Fig. S2. Interannual variability in (a) WED and (b) the proportion of immature krill as calculated in the static (circles) and dynamic ice scenario (squares).

SUPPLEMENT 3.

Converting Antarctic krill size classes into energy density and sex/maturity stages

Below, we review the methodology of Chapman et al. (2010), as well as the exceptions and assumptions that we made, to calculate the mean wet-mass energy density (WED) of krill consumed by chicks each year. We created 2 scenarios based on average sea ice conditions in the region (static scenario; sWED) and the influence of sea ice on the krill reproduction cycle (dynamic scenario; dWED). First, the length at maturity function (Siegel & Loeb 1994) calculates the proportion of mature males (m) and females (f ; $P_{m/f,n}$) in each size class (n):

$$P_{m/f,n} = \frac{1}{1 + e^{-k_{m/f}(TL_n - L_{50,m/f})}} \quad (\text{S1})$$

$k_{m/f}$ controls the rate of increase in the proportion of sexually mature krill ($k_m = 0.6$; $k_f = 0.83$; Siegel & Loeb 1994), TL_n is the mean total length (mm) of krill within each size class (n), and $L_{50,m/f}$ is the length where 50% of krill reach sexual maturity ($L_{50m} = 42$ mm; $L_{50f} = 34$ mm; Siegel & Loeb 1994). Altering these variables had no effect (<0.01 kg) on simulated CFM (Chapman et al. 2010); therefore, these parameters remained fixed.

The total proportion of mature males and females ($T_{m/f}$) in the population from size class distributions for each year was calculated as follows:

$$T_{m/f} = \sum_1^N P_{m/f,n} R_{m/f} SC_n \quad (S2)$$

$R_{m/f}$ is the sex ratio in the population ($R_m = 0.5$, $R_f = 0.5$). We assumed no active selection of female krill over males (Fraser & Hofmann 2003, Salihoglu et al. 2001). SC_n is the proportion of the krill population within each size class, which we measured from Adélie penguin diet samples. The proportion of immature krill is the proportion that was not accounted for by mature males or females.

The proportion of mature males and females that participate in spawning ($SP_{m/f}$) was calculated as follows:

$$SP_{m/f} = T_{m/f} sp_{m/f} \quad (S3)$$

$sp_{m/f}$ is the proportion of mature males and females that spawn. Variability in the percentage of male and female spawners had no effect on CFM (Chapman et al. 2010). Due to the high interannual variability of the region, between 10 and 100% of mature krill actually spawn (Siegel & Loeb 1995, Quetin & Ross 2001). The intensity of krill reproduction is a function of adequate food availability or primary production during the time of ovarian development, which has been related to spring sea ice extent and timing of ice retreat (Quetin & Ross 2001, Quetin et al. 2007). In the Palmer Station region, average sea ice extent and retreat are ideal for high reproductive output, but late retreat causes a shortage of food during ovarian development, and early retreat produces the worst conditions for primary production and krill reproduction (Quetin & Ross 2001). For the static scenario, we assumed all mature krill spawn. For the dynamic scenario, we assumed 90% of krill spawn under average ice retreat, 70% spawn under late retreat, and 50% spawn under early retreat.

Since gravid female krill lose ~54% of their lipid content during spawning (Clarke 1980), the proportion of gravid females (P_{gravid}) in the diet was calculated for each day of the chick-rearing period as follows:

$$P_{gravid}(t) = T_f e^{-(t-S_{pk})^2/S_{dur}} \quad (S4)$$

where t is time (days). Our simulation began at chick hatching (Day 1) and ended at the beginning of the starvation period (Day 50), which occurs 3 to 7 d before fledging when parents stop feeding their chicks (Trivelpiece et al. 1987, Ainley 2002, Chapman et al. 2010). S_{pk} is the peak spawning day where the maximum proportion of gravid mature females occurs, S_{dur} is the spawning duration, i.e. the period in which >50% of the spawning females are gravid, and T_f is the proportion of spawning females (Eq. S2). Before peak spawning (S_{pk}), P_{gravid} was equal to T_f , which assumed all spawning mature females were gravid. After peak spawning, the proportion of spent females was the difference between the proportion of spawners (T_f) and current proportion of gravid females (P_{gravid}). The average lipid content of a spawning female was 28% dry mass, and that of a spent female was 18% (Clarke 1980, Virtue et al. 1996, Hagen et al. 1996). For each day, the proportion of gravid/spent females was multiplied by the corresponding lipid content, and then, the sum of the product was taken. After the 50 d simulation, we computed the mean dry-mass lipid content for mature females. We did not account for interannual variability

in the length of the starvation period or duration of the chick rearing period, which could affect chick mass (Chapman et al. 2010).

According to Chapman et al. (2010), the date of peak spawning and timing of seasonal lipid accumulation had the greatest influence on CFM. For the static ice scenario, S_{pk} was set to January 20, and S_{dur} was 60 d (Quetin & Ross 2001). An early ice retreat associated with a late phytoplankton bloom can delay krill spawning due to slower oöcyte maturation (Quetin et al. 2007). Conversely, a late ice retreat and early bloom promote early spawning. For the dynamic ice scenario, peak spawning (S_{pk}) was on January 20 during an average ice retreat, S_{pk} was 2 wk later for an early retreat, and S_{pk} was 2 wk earlier for a late retreat.

Variations in S_{pk} and S_{dur} altered the amount of high-lipid gravid and low-lipid spent females in the diet. Delaying or advancing peak spawning by other time intervals (1 or 3 wk) produced WEDs within $\pm 0.1 \text{ kJ g}^{-1}$ for each year and were highly correlated ($\rho > 0.97$) to the 2 wk interval. Chapman et al. (2010) noted that changing S_{dur} (17 to 99 d) had up to a 90 g effect on CFM. Thus, we created static ice scenarios with an S_{dur} of 20 and 100 d; both scenarios produced WEDs that were within $\pm 0.1 \text{ kJ g}^{-1}$ per year and highly correlated ($\rho > 0.95$), so S_{dur} for the static ice scenario was held constant at 60 d. To approximate spawning characteristics for the dynamic ice scenario, S_{dur} was 100 d for late retreat, 20 d for early retreat, and 60 d for average retreat.

The lipid content of mature males and immature krill typically increases over the austral summer in preparation for over-wintering (Quetin & Ross 1991, Hagen et al. 1996). The lipid content of immature krill is greater than that of mature males and spent females but less than that of gravid females. We created a time-varying lipid content for mature males and immature krill based on average lipid content before and after the peak spawning date. The average lipid content before peak spawning was 10% dry mass for mature males and 16% for immature krill; after peak spawning, the average lipid content was 21% for mature males and 24% for immature krill (Clarke 1980, Hagen et al. 1996, Virtue et al. 1996). For the static ice scenario ($S_{pk} = \text{Jan 20}$), chicks consumed more krill before peak spawning than after peak spawning (64% of the total consumed krill was consumed before peak spawning vs. 36% consumed after). For the dynamic ice scenario, where peak spawning varied with the timing of ice retreat, the ratio of time (before:after) peak spawning for average, late, and early retreat was 0.64:0.36, 0.36:0.64, and 0.92:0.08, respectively. For each year, the proportion of time spent consuming male/immature krill was multiplied by the respective time-varying maturity stage lipid content. This value was the mean dry-mass lipid content for mature males and immature krill.

Lastly, dry-mass energy density (E_{kdm} ; kJ kg^{-1}) for the krill population was calculated for each year (t):

$$E_{kdm}(t) = \sum_1^n P_{ms}(t)L_{ms}(t)LED \quad (\text{S5})$$

P_{ms} is the proportion of each sex/maturity stage in the population (n), L_{ms} is the dry-mass lipid content of each sex/maturity stage, and LED is the lipid energy density, which converts lipid content to energy density ($LED = 0.0395$; Clarke 1980). We converted dry-mass energy density into WED (kJ g^{-1}) by dividing E_{kdm} by 0.216 (Ikeda & Mitchell 1982).

In estimating WED, we had to make a number of assumptions in computing the relative proportion of mature male and female krill and the proportion of spawners. Chapman et al.

(2010) found that CFM was most sensitive to variation in the timing of spawning, which we controlled for in the dynamic ice scenario by changing the timing of spawning dependent on the timing of sea ice retreat. Dynamic WED was higher and more variable than static WED, which largely resulted from changing the proportion of spawning mature krill (see Fig. S2 in Supplement 2). In contrast, altering spawning duration and peak spawning date had only a small effect on WED ($<0.1 \text{ kJ g}^{-1}$), making these WED scenarios highly correlated ($\rho > 0.95$, $p < 0.05$). We found that CFM was not correlated to sWED ($\rho = 0.08$) or dWED ($\rho = 0.07$) and was moderately correlated to the proportion of immature krill from the static ($\rho = 0.36$, $p = 0.09$) and dynamic scenarios ($\rho = 0.33$, $p = 0.11$) when 2001 was eliminated (a year of anomalous weather events). From 1987 to 2011, sWED and dWED were not correlated ($\rho = 0.10$), whereas both scenarios for immature krill were highly correlated ($\rho = 0.76$, $p < 0.05$) (Fig. S2). Additionally, dWED and the proportion of immature krill from the dynamic scenario were significant predictor variables in our stepwise regression models (see Table 1 in the main article). We expected the dynamic ice scenario to be more important because of the known influence of sea ice dynamics on the krill reproduction cycle (Quetin & Ross 2001). Therefore, we focused on the dynamic scenario for WED and the proportion of immature krill throughout this study.

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