The following supplement accompanies the article

Effect of climate variability on weaning mass in a declining population of southern elephant seals *Mirounga leonina*

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Details of the environmental variables used to explain the weaning mass of southern elephant seal pups. The variables are divided into global and regional variables

Global Climate Modes:

The high latitudes of the Southern Hemisphere experience large-scale, sub-decadal climatic variation as a result of a number of global modes of atmospheric variability present in the region, including:

Southern Annular Mode:

The Southern Annular Mode (SAM, or Antarctic Oscillation) is the dominant mode of extra-tropical atmospheric variability in the Southern Hemisphere, that acts over intra-seasonal to inter-annual timescales (Thompson & Wallace 2000, Lovenduski & Gruber 2005). The SAM is characterized by synchronous atmospheric pressure anomalies of opposite sign between the mid- and high-latitudes that drives the north-south movement of a circumpolar band of strong sub-polar westerly winds (Stammerjohn et al. 2008b). During positive SAM (+SAM) phases, positive pressure anomalies over the mid-latitudes and negative pressure anomalies over the high-latitudes drive the northward expansion and weakening of the sub-polar westerlies, while the opposite is true for negative phases of the SAM, with the subpolar westerlies contracting poleward and subsequently strengthening (–SAM; Stammerjohn et al. 2008a).

The meridional movement of these winds can have substantial effects on Southern Ocean circulation patterns and therefore have important implications for a number of associated biological and physical processes (Lovenduski & Gruber 2005). For example, during positive phases of SAM northward Ekman transport anomalies and associated upwelling of cold nutrient-rich waters stimulates phytoplankton production in the Antarctic and Polar Frontal Zones, while increases in SST and a deepening of the mixed layer depth in the sub-Antarctic Zone is associated with decreases in primary productivity in this region (Lovenduski & Gruber 2005, Schine et al. 2016).

Further, much of the inter-annual variability in sea ice extent in the Ross/Amundsen Seas and Bellingshausen/Weddell Seas has been attributed to the SAM, with positive SAM phases associated with increased sea ice growth in the Ross and Amundsen Seas and limited sea ice growth in the Bellingshausen and Weddell Seas, and vice versa for negative SAM phases (Liu et al. 2004, Stammerjohn et al. 2008b, Schine et al. 2016).

Annual SAM index values (http://www.nerc-bas.ac.uk/icd/gjma/sam.html) for the months spanning the post-moult period (Feb-Oct) were averaged to provide a broad-scale SAM index representing the climatic conditions experienced by females over their post-moult foraging migrations (Oosthuizen et al. 2015). Because no long-term datasets of chlorophyll concentration exist for the Ross Sea region over the study period, these SAM values also provide a crude proxy of primary productivity in the Antarctic and sub-Antarctic zones in this region over study period (Oosthuizen et al. 2015, Schine et al. 2016).

El-Nino – Southern Oscillation (ENSO)

Despite having tropical origins, the El-Nino – Southern Oscillation (ENSO) has a profound influence on the weather and oceanic conditions of the high latitudes of the Southern Hemisphere (Turner 2004, Schine et al. 2016). In the Ross Sea, atmospheric forcing by ENSO is associated with significant variations in sea-ice dynamics and productivity between the shelf and off-shelf regions; during cold phases of ENSO (La Nina), sea surface temperature, open water days and net primary productivity increase on the shelf and decrease off the shelf, while the opposite is true of warm ENSO phases (El Nino) (Schine et al. 2016).

The Southern Oscillation Index (SOI), defined as the twice-normalized difference in surface pressure between Tahiti and Darwin, Australia (Turner 2004), was used to determine the occurrence and strength of El Nino and La Nina events, with sustained positive SOI values above +7 indicating the occurrence of a La Nina event, while sustained negative values below -7 indicate an El Nino event (http://www.bom.gov.au/climate/glossary/soi.html). As with the SAM, SOI values for the post-moult months were averaged to provide a mean SOI value representing conditions over the post-moult period.

Regional Environmental Variation:

The following regional environmental variables (i.e. within the core foraging areas) were included as extrinsic covariates based on an *a priori* understanding of the influence that these variables have on oceanic and biological features likely to be important to the foraging success of Macquarie Island breeding females:

Sea Surface Temperature (SST)

Mean SST (ºC) within the core foraging areas was extracted from the NOAA 1/4º daily Optimum Interpolation Sea Surface Temperature (or daily OISST; https://www.ncdc.noaa.gov/oisst) and was included as an extrinsic covariate to determine whether inter-annual variations in SST in the foraging region influenced maternal foraging success and therefore the mass of a female's pup at weaning.

Sea Surface Temperature gradient (SSTg)

Sea surface temperature gradient (SSTg) was estimated from SST, by calculating the maximum rate of change across a 3 x 3 cell grid surrounding each individual cell, using the *terrain* function in *raster*. SSTg was used to indicate the presence of fronts and the convergence of local water masses within the core foraging areas. The Antarctic Circumpolar Current (ACC) has three major circumpolar fronts characterized by steep meridional gradients in SST, salinity, current speed, density and sea surface height (Bost et al. 2009, Sokolov & Rintoul 2009a). These fronts are: (1) the Subtropical Front (STF) that delimits the northern boundary of the ACC and separates warm, salty subtropical waters to the north from the cold, fresh sub-Antarctic waters to the south, (2) the Sub-Antarctic Front (SAF), and (3) the Polar Front that divides the sub-Antarctic from the Antarctic and marks the subduction of cold Antarctic Surface Waters beneath warmer sub-Antarctic waters (Sokolov & Rintoul 2002, 2009a, Sokolov & Rintoul 2009b). These fronts are often associated with aggregations of apex predators, such as seabirds and whales, due to high concentrations of prey as a result of (a) increased primary production at the front, and/or (b) because of the passive transport of prey to the front by convergent processes (Bost et al. 2009). SST gradient (SSTg; calculated from SST) therefore allowed us to quantify the influence of oceanic fronts on elephant seal weaning mass.

Sea Surface Height anomaly (SSHa)

The annual average sea surface height anomaly (SSHa; mm) was extracted for the spatial context from AVISO (http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products.html) and represented the discrimination of water masses and fronts. SSH anomalies are also indicative of eddy activity, with positive anomalies indicating the presence of upwelling, cold-core cyclonic eddies, while negative anomalies suggest the presence of down-welling, warm-core anti-cyclonic eddies (Bailleul et al. 2010)

Sea Surface Height anomaly variance (SSHv)

The annual average variance in SSHa (mm) was calculated from weekly SSHa values for each grid cell and was included as an index of eddy activity, with high SSHa variance associated with persistent meso-scale eddy activity. Measuring eddy activity is useful because eddies are thought to be oases of biological productivity in the open ocean due to relatively high productivity and prey concentrations particularly within upwelling cyclonic eddies (Davis et al. 2002, Strass et al. 2002).

Wind Strength (wind)

The turbulent mixing of the upper ocean by wind is an important determinant of the depth of the mixed layer depth (MLD; Kara et al. 2003) and has significant and complex implications for primary productivity through alterations in nutrient and zooplankton concentrations and the availability of light (Boyd et al. 2008). Wind strength data was sourced for each year from NCEP/DOE AMIP-II (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm).

Surface Currents (Sc):

AVISO ocean current data (m/s; http://www.aviso.altimetry.fr/en/home.html) was extracted for the spatial domain to determine the effect of surface current strength on southern elephant seal foraging success and offspring weaning mass.

Sea Ice Concentration (ice-c)

We used mean sea ice concentration sourced from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data (version 1; Cavalieri et al. 1996, updated yearly.) to determine whether ice coverage in the core foraging areas of adult females affects the size of their pups at weaning. Sea ice concentration was expressed as the percentage (%) of ocean covered by ice within each grid cell.

Sea Ice Extent (ice-e)

To quantify how sea ice extent affects the weaning mass of Macquarie Island seals, we used the median northerly sea ice extent in August (expressed as latitudinal degrees) for each year for the area between 120^{o} to 230^{o}W and 40^{o} to 75^{o}S. Sea ice extent data was derived using the blended optimal interpolation Version 2 Ice Extent Estimate from the integration of the daily Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and Advanced Very High Resolution Radiometer (AVHRR) 0.25^{o} global ice charts (Parkinson & Cavalieri 2012)   Median sea ice extent in August was used as August has previously been identified as the month when sea ice in our study region reaches or is close to its annual maximum extent (McMahon et al. 2016).

Statistical Analyses

Linear models (LMs) were fitted to the data using the *stats* package in the statistics program R (version 3.1.1; R Core Team, 2016) to quantify how extrinsic and intrinsic covariates affect elephant seal weaning mass. After first fitting the null (intercept) model, we fitted a series of models of increasing complexity that related intrinsic covariates (i.e. *sex, m.size and l.fem*) to weaning mass. Extrinsic covariates explaining between-year variations in weaning mass (e.g. SAM, SOI, SST) were then added sequentially to the top model from the suite of models previously constructed using only the intrinsic covariates.

Given that the number of statistical units available to detect the influence of covariates on elephant seal weaning mass was the number of years of data available (i.e. 7; Grosbois et al. 2008), we restricted each model to the top model explaining intrinsic variation in weaning mass plus a single environmental (extrinsic) covariate. By keeping the ratio of covariates to statistical units low, we minimized the likelihood of detecting spurious climatic effects (i.e. Type I error; Grosbois et al. 2008). All model parameters were fitted using Maximum Likelihood (ML) estimation. Model selection was based on corrected Akaike's information criterion (AICc; Burnham et al. 2011).

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