**Supplementary Materials**

Figs. S1 to S4



*Figure S1. 2-D density plot, illustrating results of Bayesian posterior predictive checks to evaluate goodness-of-fit. Darker shades indicate a larger number of Monte Carlo simulations.*



*Figure S2. Comparison of raw (observed) data and modeled indices of abundance at 50 emperor penguin colonies.*



*Figure S3. Results of 1000 Monte Carlo simulations in which time series of abundance (and aerial and satellite observations) were simulated at all colonies, resulting in simulated global trajectories, that were then re-estimated using our statistical model. Simulation results indicate the model can reliably recover simulated global trends.*



*Figure S4. Results of re-estimating 10-year population change estimates across 1000 Monte Carlo simulations in which time series of abundance (and aerial and satellite observations) were simulated at all colonies, resulting in simulated global trajectories, that were then re-estimated using our statistical model. Simulation results indicate the model can reliably recover simulated global trends.*

Tables S1 to S4

Table S1. Description of emperor penguin population model. Colony indexed by *j*, year by *y*, observation event *i*.

|  |  |  |
| --- | --- | --- |
| Description | Equations |  |
| *Population process model* |
| Abundance of adults ($N\_{j,y}$) is the product of a colony-level presence/absence process ($z\_{j,y}$) and a stochastic exponential growth process ($X\_{j,y}$).$N\_{j,y}$ measures expected (i.e., mean) daily number of adults in the colony during survey period (Sep – Nov). | $$N\_{j,y}= z\_{j,y}X\_{j,y}$$ | (1) |
| Colony presence is a Bernoulli process controlled by a “probability of presence” parameter $p$ | $$z\_{j,y}\~ Bernoulli(p)$$ | (2) |
| When colonies are present, they fluctuate according to a stochastic exponential Markov chain process, with a colony-specific mean annual change $r\_{j}$. | $$X\_{j, y} \~ Lognormal\left( log⁡(X\_{j, y-1}\right)+r\_{j} , σ\_{process}^{2})$$ | (3) |
| *Aerial survey observation model* |
| Counts of adults from aerial surveys ($A\_{j,y,i}$) are centered on the expected count ($z\_{j,y}X\_{j,y}$), adjusted by an effect of day-of-year of the survey ($DOY\_{j,y,i}$) | $A\_{j,y,i} \~ Poisson(z\_{j,y}λ\_{j,y,i})$, where$$λ\_{j,y,i} \~ Lognormal\left(log⁡(X\_{j, y})+α×DOY\_{j,y,i}-\frac{1}{2}σ\_{aerial\\_obs}^{2} ,σ\_{aerial\\_obs}^{2}\right)$$ | (4) |
| *Satellite survey observation model* |
| Satellite counts are potentially biased ($β$), have error proportional to colony abundance, and depend on the day-of-year of the survey (DOY).  | $$S\_{j,y,i} \~ Normal\left(βN\_{j,y}exp(α×DOY\_{j,y,i}) , ω\_{j,y}^{2}\right)$$ | (5) |

*Table S2. Parameter symbols correspond to those in Table S1.*

|  |  |
| --- | --- |
| **Prior** | **Rationale** |
| $$p \~ Uniform(0,1)$$ | Diffuse prior for probability that colony is present each year. |
| $$\overbar{X}\_{1}\~ Uniform(0,50000)$$$$\frac{1}{σ\_{logX\_{1}}^{2}} \~ Gamma(0.001,0.001)$$ | Diffuse prior for median baseline abundance (i.e., the median across all colonies). The baseline abundance at each colony is a random effect, varying around $\overbar{X}\_{1}$. |
| $$\overbar{r} \~ Normal(0,1)$$$$\frac{1}{σ\_{r}^{2}}\~Gamma(0.001,0.001)$$ | Weakly informative prior for $\overbar{r}$; values of $\overbar{r}$ extremely far from 0 are biologically impossible. Diffuse prior for variance in colony-level growth rates. |
| $$\frac{1}{σ\_{process}^{2}}\~Gamma(0.001,0.001)$$ | Diffuse prior for lognormal temporal variance in population indices |
| $$\frac{1}{σ\_{aerial}^{2}}\~Gamma(0.001,0.001)$$ | Diffuse prior for lognormal standard deviation of aerial observations. |
| $$β \~ Normal(1, 0.2)$$ | Weakly informative prior for the relationship between number of adult penguins and ground area of pixels classified as penguins. The relationship should have a near 1:1 relationship given the coarseness of satellite resolution (~1 m), so we centered prior on 1. Bias of more than +/- 20% should be moderately unlikely, and bias more than +/- 40% should be extremely unlikely, so we specified a standard deviation of 0.2 for the prior. |
| $$CV\_{satellite} \~ Uniform(0,2)$$ | Diffuse prior for coefficient of variance in satellite counts. Values of CV greater than 2 are unlikely and subsequent evaluation of posterior confirms that CV is far less than 2. |
| $$α \~ Normal(0,0.2)$$ | Weakly informative prior for the fixed effect of day-of-year on which observation was collected.  |

*Table S3. Summary of parameter estimates governing population dynamics. Parameter symbols correspond to those described in Tables 1 and 2. ESS denotes the effective sample size of posterior samples resulting from the MCMC sampler in JAGS.*

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Mean** | **SE** | **2.5%** | **25%** | **50%** | **75%** | **97.5%** | $$\hat{R}$$ | **ESS** |
| *Parameters describing population process* |
| $$p$$ | 0.96 | 0.01 | 0.94 | 0.95 | 0.96 | 0.97 | 0.98 | 1.00 | 30000 |
| $$\overbar{r}$$ | -0.033 | 0.02 | -0.073 | -0.046 | -0.032 | -0.019 | 0.007 | 1.00 | 17204 |
| $$σ\_{r}$$ | 0.040 | 0.02 | 0.018 | 0.029 | 0.037 | 0.048 | 0.076 | 1.00 | 30000 |
| log($\overbar{X}\_{1})$ | 8.07 | 0.19 | 7.70 | 7.94 | 8.07 | 8.19 | 8.43 | 1.00 | 30000 |
| $$σ\_{logX\_{1}}^{2}$$ | 1.16 | 0.13 | 0.93 | 1.07 | 1.15 | 1.24 | 1.45 | 1.00 | 21739 |
| $$σ\_{process}$$ | 0.35 | 0.04 | 0.27 | 0.32 | 0.35 | 0.38 | 0.43 | 1.00 | 30000 |
| *Parameters describing observation process* |
| $$σ\_{aerial}$$ | 0.44 | 0.04 | 0.37 | 0.41 | 0.43 | 0.46 | 0.51 | 1.00 | 30000 |
| $$CV\_{satellite}[quality=1)$$ | 0.42 | 0.05 | 0.34 | 0.39 | 0.42 | 0.45 | 0.52 | 1.00 | 18556 |
| $$CV\_{satellite}[quality=2)$$ | 0.49 | 0.04 | 0.42 | 0.46 | 0.49 | 0.52 | 0.58 | 1.00 | 14284 |
| $$CV\_{satellite}[quality=3)$$ | 0.35 | 0.03 | 0.29 | 0.33 | 0.35 | 0.37 | 0.41 | 1.00 | 30000 |
| $$β\_{satellite}[quality=1)$$ | 0.88 | 0.08 | 0.74 | 0.82 | 0.87 | 0.93 | 1.03 | 1.00 | 11375 |
| $$β\_{satellite}[quality=2)$$ | 0.89 | 0.08 | 0.74 | 0.83 | 0.88 | 0.94 | 1.04 | 1.00 | 6168 |
| $$β\_{satellite}[quality=3)$$ | 1.07 | 0.08 | 0.91 | 1.01 | 1.07 | 1.12 | 1.24 | 1.00 | 5624 |
| $$α$$ | -0.004 | 0.001 | -0.006 | -0.004 | -0.004 | -0.003 | -0.001 | 1.00 | 30000 |

Table S4. List of emperor penguin colony locations with apparent colony absences over the study period (2009 to 2018), including the name of the colony, the Catalog ID, which is the unique identifier of the VHR image on which the absence was observed (courtesy Maxar Technologies), the date of the image, and relevant notes about observations.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site ID | Colony | Catalog ID | Date (MM/DD/YYY) | Notes about image |
| AMUN | Amundsen Bay | 101001000C67CB00 | 10/08/2010 | No penguins were evident |
| AMUN | Amundsen Bay | 103001001B5D6900 | 09/10/2012 | No penguins were evident |
| BBAY | Barrier Bay | 103001000FBFAF00 | 11/26/2011 | Cannot see birds |
| BBAY | Barrier Bay | 1020010079BE4100 | 09/30/2018 | Ice shelf looks like it is breaking up |
| BEAN | Beaufort Island | 101001001073DA00 | 10/17/2012 | Ice has broken out already |
| LEDD | Ledda Bay | 101001000A842D00 | 10/27/2009 | No fast ice |
| LEDD | Ledda Bay | 103001000D47DA00 | 09/23/2011 | Fast ice available |
| LEDD | Ledda Bay | 10504100002F7500 | 10/22/2012 | No fast ice |
| LEDD | Ledda Bay | 1030010036A28700 | 10/13/2014 | Fast ice available, no birds |
| LEDD | Ledda Bay | 103001004C94D400 | 11/13/2015 | Fast ice available, no birds |
| LEDD | Ledda Bay | 1020010052041500 | 08/25/2016 | No fast ice |
| MERT | Mertz Glacier | 102001000F512400 | 10/02/2010 | Location for Mertz after glacier broke off |
| RUPE | Rupert Coast | 1040010013AFB500 | 10/29/2015 | No evidence of birds anywhere |
| RUPE | Rupert Coast | 104001002153B400 | 09/13/2016 | No evidence of birds anywhere |
| SANA | Sanae | 102001001D7ACE00 | 09/24/2012 | No penguins were evident |
| UMBE | Umbeosi | 101001000C4F6A00 | 09/19/2010 | No penguins were evident |
| UMBE | Umbeosi | 101001000E11BC00 | 09/06/2011 | No penguins were evident |
| UMBE | Umbeosi | 101001001050A300 | 09/27/2012 | No penguins were evident |
| UMBE | Umbeosi | 1030010087AE1800 | 10/17/2018 | No penguins were evident |
|  |  |  |  |  |