



Shy albatross *Thalassarche cauta* chick mortality and heat stress in a temperate climate

Claire Mason^{1,2,*}, Alistair J. Hobday², Rachael Alderman³, Mary-Anne Lea¹

¹Institute for Marine and Antarctic Studies, Battery Point, Tasmania 7004, Australia

²CSIRO Environment, Battery Point, Tasmania 7004, Australia

³Tasmanian Government, Hobart, Tasmania 7001, Australia

ABSTRACT: With increasing air temperatures and frequency of extreme weather events predicted under climate change, ground-nesting seabird chicks are vulnerable, enduring months at a fixed and often completely exposed nest site, with limited behavioural capacity to reduce heat load. Endangered shy albatross *Thalassarche cauta* breed in temperate southern Australia, a region warming at about 4 times the global average. We used a remote-monitoring camera to obtain the daily status for ~150 nests each season for 7 seasons (2014–2015 to 2020–2021; 1036 nests in total), allowing clear determination of the date of chick death. We explored local weather conditions associated with chick mortality. We observed 68 downy chick deaths (55%) across a 30 d period in 2018. This period corresponded with anomalously high and prolonged wet bulb temperature, an index for heat stress. We show that shy albatross breeding attempts are vulnerable to hot weather conditions and define extreme heat stress conditions for this species (>20° wet bulb temperature). Documenting the relationship between chick survival and heat before future catastrophic events occur gives managers time to plan for future heatwaves by developing climate adaptation strategies for seabird populations.

KEY WORDS: Thermoregulation · Climate change · Heatwaves · Seabirds · Temperature extremes · Survival

1. INTRODUCTION

Endotherms use a variety of behavioural and physiological responses to maintain homeostasis when experiencing conditions outside their range of comfort (Boyles et al. 2011). Under climate change, there has been a shift in climate averages as well as increasing frequency and severity of extreme climatic and weather events (IPCC 2022). Consequently, there is growing evidence documenting the direct effects of challenging abiotic conditions on the survival, fitness, and reproductive performance of many species (Oswald & Arnold 2012, Andreasson et al. 2020). Thus, an increasing number of species will face increased thermoregulation demand and fitness trade-offs from behavioural responses as climate change in-

tensifies (Boyles et al. 2011, Cohen et al. 2020, Cunningham et al. 2021).

Seabirds in ground-nesting colonies have significant thermoregulation challenges. During the breeding season, adults and chicks stay on exposed nests, usually with no shade, for extended periods of time, withstanding extreme abiotic conditions (Oswald & Arnold 2012). Seabirds are adapted to wet and cold oceanic conditions, rendering them vulnerable to warming environments under climate change. For seabird species inhabiting warmer temperate climates, biological thresholds may be surpassed earlier as temperatures increase (Stone et al. 2021). In recent years, mass mortality events of adult seabirds have been documented as a direct result of heat (Holt & Boersma 2022, Quintana et al. 2022). Seabird chicks

*Corresponding author: claire.j.mason@csiro.au

[§]Advance View was available February 8, 2024

© M.-A. Lee and The Commonwealth of Australia 2024. Open Access under Creative Commons by Attribution Licence. Use, distribution and reproduction are unrestricted. Authors and original publication must be credited.

Publisher: Inter-Research · www.int-res.com

have a higher vulnerability to thermal stress as they are still developing their thermoregulation abilities (Stone et al. 2021), and many species can be constrained to a nest for months. Furthermore, the natal down feathers of many seabird chicks are highly effective at insulating against heat loss i.e. adapted for cold and windy climates, providing greater demand on thermoregulation mechanisms (Stone et al. 2021). Behaviours to reduce exposure to heat (e.g. seeking shade) often are not possible, and thermoregulatory behaviours such as panting and gular fluttering are energetically costly.

The shy albatross *Thalassarche cauta* is a temperate seabird located in southeast Australia, a region warming at about 4 times the global average (IPCC 2021). Recently uplisted to endangered under Australian legislation, climate change is listed as an imminent threat for this species (Thomson et al. 2015, Alderman & Hobday 2017). Albatross Island is the second largest of 3 shy albatross populations, containing ~40% of the global population (Alderman et al. 2011, Department of Natural Resources and Environment Tasmania unpubl. data), and as the most northerly distributed population (Southern Hemisphere), it has the greatest exposure to high temperatures. Untangling the climate dependencies of this species is a knowledge gap for assessing the conservation status of shy albatross, especially the influence of local weather on breeding attempts. In this study, we test the influence of weather on temporal patterns of shy albatross chick mortality at Albatross Island.

2. MATERIALS AND METHODS

2.1. Chick mortality data and survival analysis

In 2013, we trialled and installed a remote monitoring camera to observe shy albatross breeding attempts in the southernmost section of a sub-colony on Albatross Island (40° 22' 38" S, 144° 39' 20" E), Australia (Lynch et al. 2015). Beginning with the subsequent austral summer breeding season of 2014–2015 and continuing through the 2020–2021 season, we processed daily high-resolution photographs to determine the status of 86–224 nests annually (see Table 1). We excluded nests from our survival data if no chick was seen. In these cases, either no breeding attempt was made or the attempt failed during incubation. It is unlikely that chick deaths were missed, as the adults regularly shift on the nest, giving a clear view of the nest bowl. The date of a chick's death was clear from the images (see Supplement 1; all supple-

ments are found at www.int-res.com/articles/suppl/m737p137_supp.pdf). In very few cases, a chick disappeared well before the age of fledging and the chick's corpse was not captured by the camera. In these cases, we assumed that the carcass was scavenged after a natural mortality event and before the daily image was taken on the next day, as there are no predators on the island that would commonly take live chicks. We included these events in our data. We modelled the survival of shy albatross chicks from hatching until leaving their nest site, unless otherwise censored by camera operation failing before the time of fledging.

We used survival analysis for our data, as the 'event' (i.e. chick death) was right-censored (Clark et al. 2003). To format our data for survival analysis (Clark et al. 2003), we dated time-to-event from 1 November (the earliest day a live chick was observed over all seasons) in each season. We used a fixed date across all seasons, as there is little variation in the timing of the breeding cycle for shy albatross (Hedd & Gales 2005, Department of Natural Resources and Environment Tasmania unpubl. data). The event for each nest was dated as the date of chick death or censored at the end of the camera deployment for that season. In 2015–2016 and 2016–2017, data ended 30 January and 22 February, respectively; therefore, data were censored many months before chicks fledged, providing significantly reduced data coverage for these 2 seasons. In 2018–2019 and 2019–2020, the camera outlasted the fledging period, so we censored all remaining live nests (including those that had fledged) on 1 June, 1 week after the maximum date that we observed a chick leaving their nest site across all years (23 May).

We used Kaplan-Meier survival models using package 'survival' (v.3.5.5; Therneau & Grambsch 2000, Therneau 2021) in R to model the survival probability of shy albatross chicks over time for each season. The Kaplan-Meier method is a non-parametric technique for estimating survival probability as a function of time. It assumes that the event of interest occurs at a clearly defined time, all events occur independently, and the survival probability of all observations (including censored observations) is equal (Kaplan & Meier 1958). To summarise: the survival probability tells you the probability of surviving beyond a certain time, the cumulative hazard function tells you the accumulated risk of experiencing the event up to a certain time, and the hazard function gives you the instantaneous risk of experiencing the event at a specific time, given survival up to that point (Bradburn et al. 2003a,b).

We used the package 'muhaz' (v.1.2.6.4; Hess 2021) in R to produce a smoothed estimate of the hazard function. The hazard function is estimated from smoothing splines from the cumulative hazard function. Using this function, we can visualise the instantaneous risk of the event occurring for each time point; in our case, risk of chick mortality for each day of the study. We used the hazard function instead of daily counts of deaths because the hazard function is useful for visualising the failure process and it clearly shows when mortality rates deviate from stationary. This is useful to compare years and look for 'spikes' in mortality that could be associated with extreme weather. In addition, we explored time-variable covariates (i.e. weather events) and different time intervals for each year (censored data), both of which are better incorporated with the hazard function. Finally, the hazard rate incorporates information about the number of individuals 'at risk', or chicks remaining alive at each point in time.

2.2. Weather data

The closest meteorological station to the study site is Cape Grim, operated by the Australian Bureau of Meteorology, ~18 nautical miles (34 km) southwest of Albatross Island. We obtained half-hourly meteorological data recorded at Cape Grim including wet bulb temperature (WBT), an index for heat stress, for the temporal range of our mortality data.

To capture fine-scale local weather patterns and events, we installed a small weather station on Albatross Island (ATMOS 41 weather station and EM60G Data logger, METER Group). A total of 12 meteorological parameters were captured at either 15 min or hourly resolution. However, due to its remote location, low visitation, and technical difficulties, this station provided intermittent coverage from August 2018 onwards. To estimate the relationship between the continuous Cape Grim data and the local weather station, we explored the relationship between the 2 stations (Supplement 2).

2.3. Heat stress and mortality rate

To test the hypothesis that extreme heat stress conditions increase the death rate of shy albatross chicks, we compared the hazard rate of days with heat stress conditions (WBT) in the highest 5% to all other days. We chose 5% to reflect extreme WBT conditions as per our biological hypothesis. However, we did not

choose a smaller value to ensure adequate samples, with both providing reliable estimations of the mean hazard rate in each category. The hazard rate data were not normally distributed; therefore, we compared the distribution between the 2 groups using a Mann-Whitney *U*-test. We tested for the alternative hypothesis that hazard rates in the extreme heat stress index group were higher. We applied the continuity correction as recommended for small sample sizes. All analysis and creation of graphics were undertaken using R (v.4.3.1; R Core Team 2023).

3. RESULTS

3.1. Temporal patterns in chick mortality

We recorded 430 chick deaths out of 1036 chicks monitored in our data set (Table 1, Figs. 1 & 2). In a 1 mo period (9 January–9 February 2018), 68 chicks in our study died (55% remaining chicks). This corresponded with an extended period in which the WBT (heat stress index) was in the 99th percentile of the meteorological data recorded during our study (Fig. 3).

We compared the hazard rates across WBT conditions recorded during our study by comparing lower heat-stress days with the highest 5% of heat-stress days (>19°C WBT; Fig. 4). Days with the most extreme heat-stress values had a statistically higher mean hazard rate (i.e. risk of shy albatross chick mortality) compared to lower heat-stress days ($U = 3604$, $p = 0.005$). However, as observed in Fig. 4, the most extreme days of mortality risk did not have a daily maximum WBT measurement over 19°C WBT (top 5%). Therefore, this relationship did not persist under all conditions and is likely influenced by cumulative heat stress across multiple days.

Table 1. Data summary and pattern description for shy albatross *Thalassarche cauta* chicks observed and corresponding mortality rate across 7 breeding seasons, captured by the CSIRO Ruggedised Automated Gigapixel System (CRAGS) at 'South colony' on Albatross Island, Australia (40° 22' 38" S, 144° 39' 20" E)

Season	Total no. of chicks	Chick mortality % (n)
2014–2015	90	6.7 (6)
2015–2016	86	23.3 (20) ^a
2016–2017	86	16.3 (14) ^a
2017–2018	135	65.9 (89)
2018–2019	194	40.2 (78)
2019–2020	221	48.9 (108)
2020–2021	224	51.3 (115)

^aData coverage did not last the full season

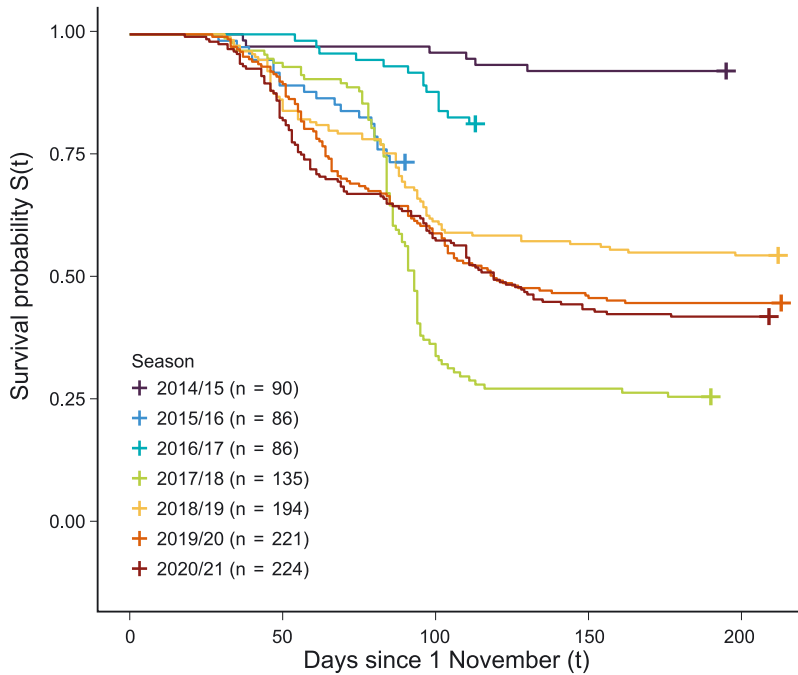


Fig. 1. Kaplan-Meier survival probability for shy albatross *Thalassarche cauta* chicks captured by the CSIRO Ruggedised Automated Gigapixel Camera System (CRAGS) across 7 breeding seasons on Albatross Island, Australia (40° 22' 38" S, 144° 39' 20" E)

We explored Cape Grim weather observations in the 15 yr prior to our study period to underline the exceptionality of the extremely high temperatures observed in 2018 (Fig. 5). It is worth noting that Albatross Island conditions could experience greater heat stress conditions than those reported in our study according to the discrepancies we observed between Cape Grim data we used in analysis and the local weather station data collected (Supplement 2).

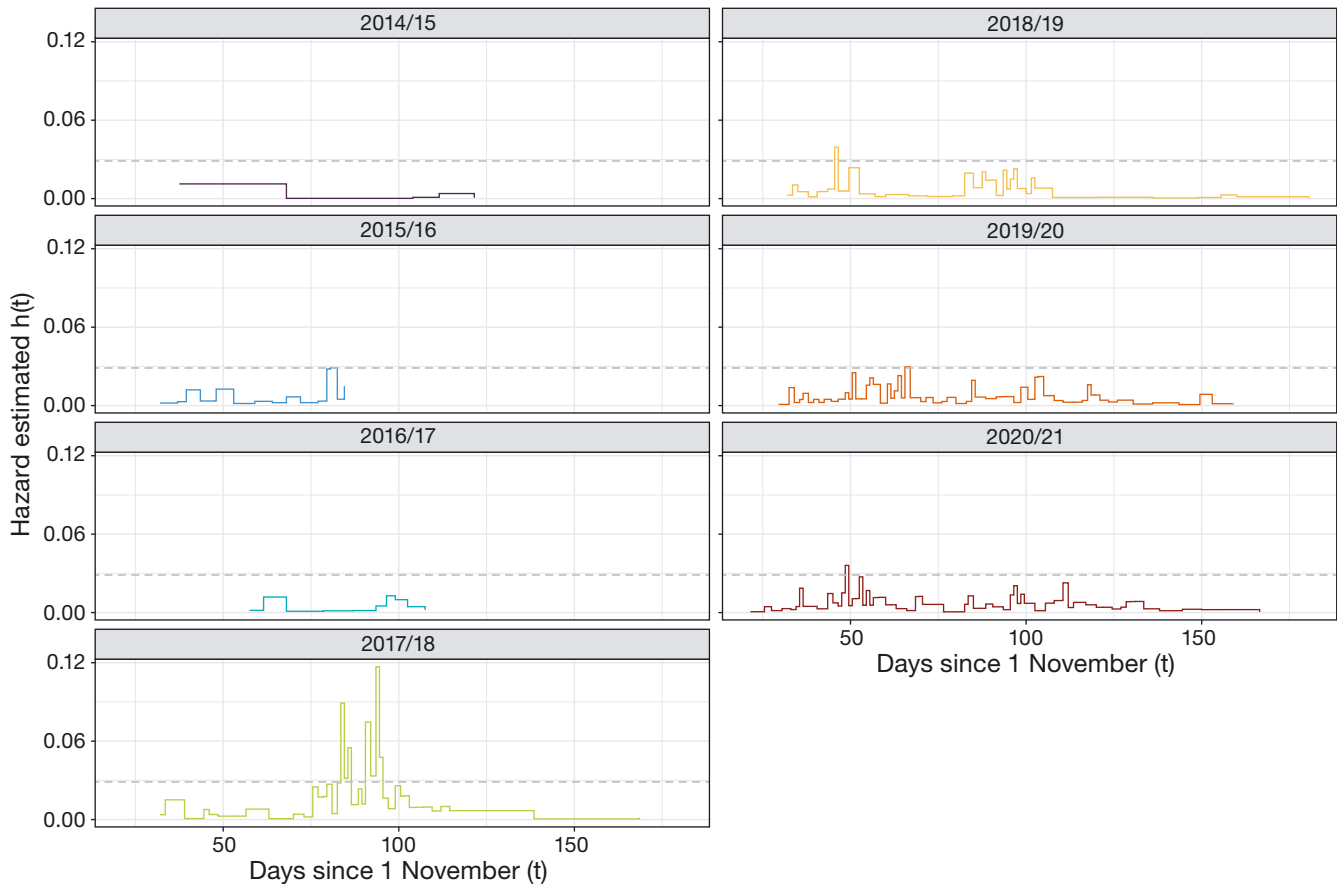


Fig. 2. Smoothed hazard function (cubic spline) from the Kaplan-Meier survival rate for shy albatross *Thalassarche cauta* chick mortality across 7 seasons (2014–2015, n = 90; 2015–2016, n = 86; 2016–2017, n = 86; 2017–2018, n = 135; 2018–2019, n = 194; 2019–2020, n = 221; 2020–2021, n = 224) on Albatross Island, Australia (40° 22' 38" S, 144° 39' 20" E). Dashed grey line: the 95th percentile hazard rates in our data for chick mortality

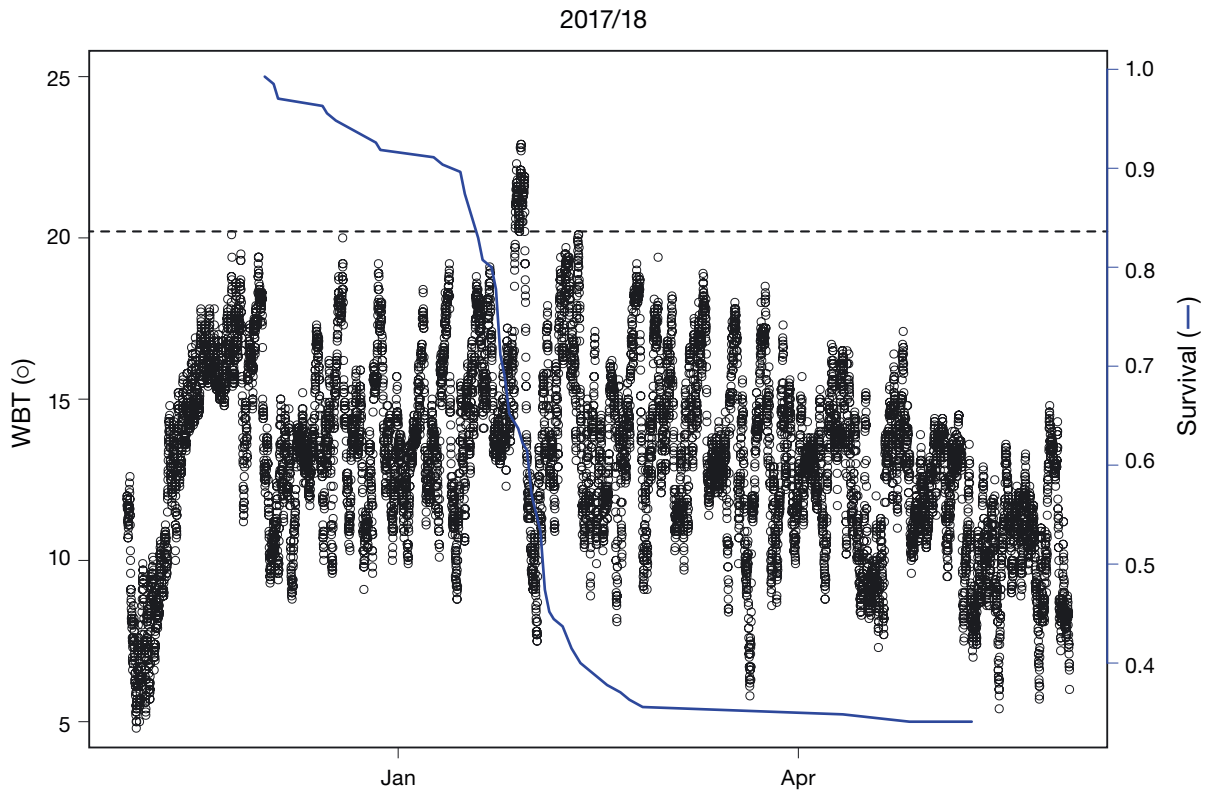


Fig. 3. Temporal overlap visualisation between chick mortality and high heat stress during the large shy albatross chick mortality event. Blue line: Kaplan-Meier survival curve of shy albatross chick mortality (right y-axis) during the 2017–2018 summer (late January–early February 2018). Black circles: half-hourly wet bulb temperature (WBT, left y-axis) from Cape Grim. Horizontal dashed line: temperatures in the 99th percentile recorded during our study (2014–2021)

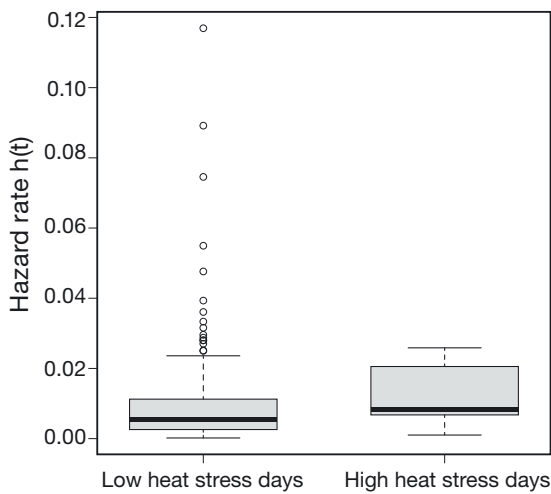


Fig. 4. Hazard rates of daily maximum daily maximum wet bulb temperatures (WBT) ($n = 238$ d) from Cape Grim split by the 95th percentile (19°C WBT) into low heat stress days of $<19^{\circ}\text{C}$ WBT and high heat stress days of $>19^{\circ}\text{C}$ WBT. Bar in box: median; box: interquartile range between the 25th and 75th percentiles; whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the box; open circles: outliers

4. DISCUSSION

We present a significant relationship between shy albatross chick survival and extreme values of the heat stress index. We documented a large mortality event of 68 deaths within 30 d (55% of remaining chicks) which coincided with extreme weather conditions (Fig. 3) that had only occurred briefly in the 2 decades prior (Fig. 5). We present new evidence on the direct and fatal impacts of climate change on shy albatross chicks.

Heat stress has been shown to impact the breeding success and survival of other animal populations, including birds (van de Ven et al. 2020a, Gardner et al. 2022) and mammals (Welbergen et al. 2008, Woodroffe et al. 2017, van de Ven et al. 2020b, Mo et al. 2021). With air temperatures predicted to continue to rise under climate change, this is a concern for cold-adapted species like albatrosses, particularly those at low latitudes that are already close to their thermal limits (Oswald & Arnold 2012). The Albatross Island colony of shy albatross in tem-

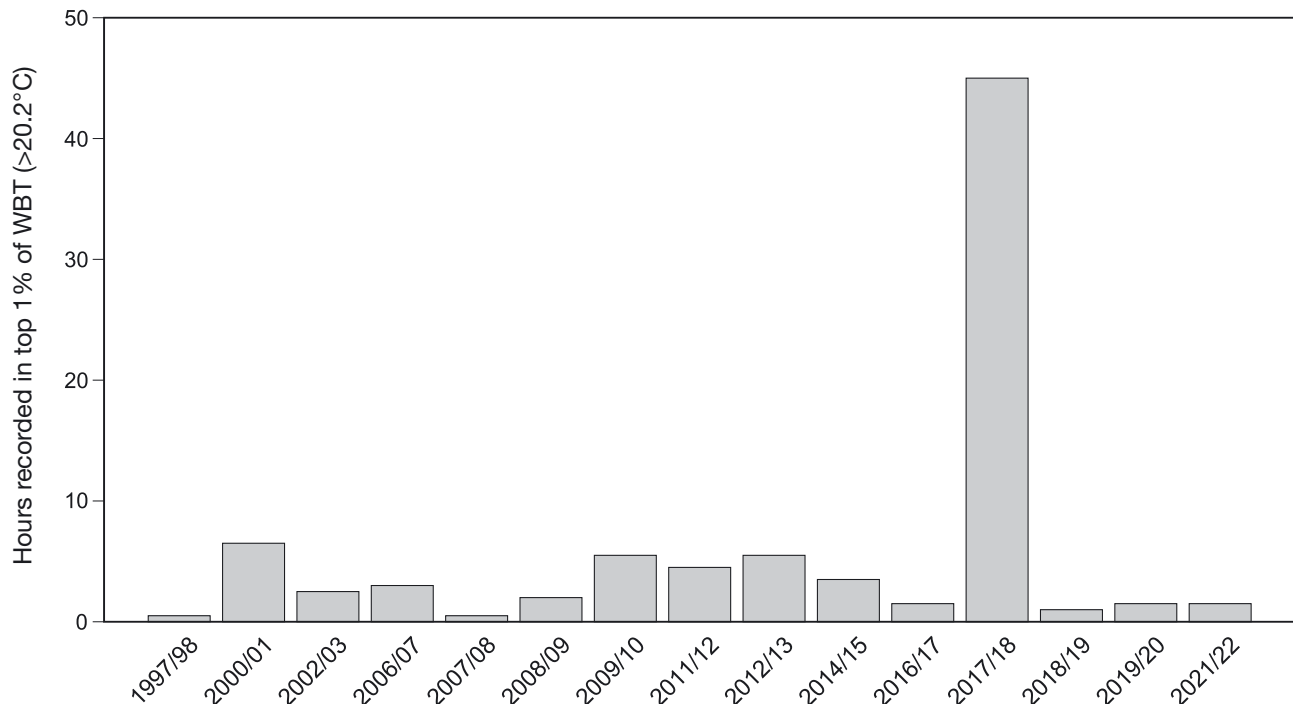


Fig. 5. Historical wet bulb temperature (WBT) data from Cape Grim station since 1997, the amount of time (in hours) each breeding season (1 November–31 May) that was recorded in the 99th percentile of daily maximum WBT temperatures recorded during our study (>20.2°C)

perate Australia studied here is at a relatively low latitude compared to most albatross species that breed in the subantarctic Southern Ocean, with the exception of the 4 Pacific *Phoebastria* species (Suryan et al. 2008). Extreme heat has directly caused mass mortality events for other colonial nesting seabirds, including cormorants (Quintana et al. 2022) and penguins (Holt & Boersma 2022), located at latitudes (43° and 44° S, respectively) similar to shy albatross from this colony (40° S). Alongside increasing average temperatures, increasing frequency and intensity of extreme events are also predicted impacts of climate change, causing physical stress that can kill or significantly impair biological functioning (Welbergen et al. 2008, Babcock et al. 2019, Smale et al. 2019, Neilson et al. 2020, Murali et al. 2023). In the case of the shy albatross, our results indicate that extreme events (Fig. 3) provide a greater impact on breeding success than average temperatures (Fig. 4), as has been shown with other wildlife populations (Marcelino et al. 2020). These distinct impacts of extreme events have implications for conservation efforts and planning (Maxwell et al. 2019). Thus, there is greater complexity occurring on high mortality-hazard days, which is not comprehensively explained by the daily maximum WBT alone (outliers in Fig. 4).

The frame of the camera captured a small section of the Albatross Island colony (~3% of breeding pairs), and we observed that spatial variation in chick mortality across the island does occur (Mason 2023). Exploring spatial variation in breeding success of this species, both on Albatross Island and for the southern populations (Mewstone and Pedra Branca), is a valuable research question to understand factors driving survival and fecundity and to identify terrain characteristics that could provide refugia from heatwave events.

4.1. Refuting other causes of mortality

Using remote methods, we could not examine carcasses to refute other causes of mortality; however, there are several reasons why we think heat stress is the most likely cause in our study. Mortality events occurring at the same time each year would suggest a developmental or age-related vulnerability. However, our 'high-stress days' occurred at different times each year (Fig. 2), suggesting an external driver. In a concurrent study of the foraging behaviour of shy albatross at this colony (Mason et al. 2023), we did not detect interannual spatial variation in foraging behaviour that would suggest adults were having diffi-

culty finding sufficient food and possibly compromising chick health and condition.

Avian pox can affect the fitness and resilience of chicks throughout the season on Albatross Island (Woods 2004) but has not been shown to directly cause mortality. For shy albatross, there is no understanding of the interactions between local weather, temperature, and the incidence of avian pox or other emerging diseases. Understanding the potential compounding and complex interaction of disease and heat stress under climate change is a future research and management priority.

4.2. Scale of monitoring and detection abilities

Mortality from heat stress occurs when physiological and behavioural adaptations are exhausted. However, prior to the lethal impacts of heat stress, sublethal effects can occur that involve behavioural, energetic, and physiological costs (Oswald & Arnold 2012, Cook et al. 2020), and in some cases, cascading population-level effects (Jenouvrier et al. 2018, Eastwood et al. 2022). The shy albatross population monitoring program comprises 2 annual visits to the colony, at the start and the end of the breeding season (Department of Natural Resources and Environment Tasmania unpubl. data). The coarseness of this data means that although overall breeding success and population dynamics can be calculated, finer-scale data, including temporal trends in breeding attempt failures, cannot be captured. Our ability to monitor chick survival and to investigate the potential impact of weather conditions was possible using high image quality and daily images of nest status from remote cameras. One limitation in using imagery is that we can only capture overt mortality events; however, it is important to also consider sublethal impacts when quantifying climate change effects. Other types of technological methods, such as thermal imaging, can provide insights into the preceding physiological and energetic costs of heat stress (McCafferty et al. 2021). Furthermore, future work exploring shy albatross thermal physiology should include wind measurements from a local weather station to provide a heat stress index that more accurately represents local variation at meaningful scales for shy albatross. Remote weather stations may not accurately represent local wind conditions at the colony, as evidenced by local and remote wind observations having the lowest R^2 value of the weather variables that we compared (Fig. S2 in Supplement 2).

4.3. Future applications

Our research shows that shy albatross chicks are a taxa and age class vulnerable to heat stress. Furthermore, as they inhabit a global warming hotspot (Hobday & Pecl 2014), they could be approaching thermal and physiological thresholds sooner than other comparable taxa around the world. Managing shy albatross populations will be necessary in the future, as even with radical action on climate mitigation, it is likely that future weather conditions will provide stresses above this species' threshold.

The relationship between heat stress and chick mortality provides evidence to support the necessity of pre-emptive management actions for this threatened species. The growing capacity for reliable and early predictions of extreme events (Jacox et al. 2022) will be critical in developing triggers for timely management action to reduce risk and mitigate impacts. A future application of this work could be the development of an 'early warning system' to predict unfavourable conditions for shy albatross, with enough lead time to deploy a climate adaptation intervention for heat stress such as erecting shade structures or water sprinklers. For flying foxes, another heat-sensitive species in Australia, a spatially explicit forecaster for heat-related mortality events has proven to be a successful trigger for local management intervention (Ratnayake et al. 2019). For this model to be properly developed for shy albatross, a local weather station would be of priority to capture the real-time conditions that are occurring on Albatross Island. Further work determining the reliability of different time lags would be important, as balancing the forecast accuracy with ample lead time would be an important trade-off to explore. Our results allow for accurate forecasts of the population's resilience under future conditions alongside a tangible meteorological value for conditions that are likely biologically stressful for shy albatross chicks.

Data archive. Cape Grim historical weather observations are available on request from BOM Data Services www.bom.gov.au/climate/data-services/station-data.shtml. Chick mortality data, Albatross Island weather station data, code to recreate analyses and figures in R, and video grab showing chick death with CRAGS technology are available at <https://github.com/clairemas0n/hot-chicks>.

Acknowledgements. We acknowledge the palawa peoples of lutruwita, the traditional and ongoing custodians of the unceded lands on which this work was completed. This research was possible by the development and successful operation of the CSIRO Ruggedised Automatic Gigapixel Camera System (CRAGS) and our appreciation goes to CSIRO

and all who have worked on this system, especially Carlie Devine. This research relies on the dedicated work of the Marine Conservation Program (Tasmanian State Government) staff and volunteers who facilitate, organise, and enable research and fieldwork, maintain the long-term demographic monitoring program that supports and underpins this research, and assist with the operation and maintenance of CRAGS and the Albatross Island weather station. Thank you to Camille Couzi and Milan Sojitra, who processed images. We appreciate the discussions and advice from Dahlia Foo and Dominic McCafferty, which helped to develop the methods and ideas in the manuscript. Thank you to Sheryl Hamilton for comments on the draft. Thank you to the reviewers and editors at MEPS, particularly Rob Suryan, for your thorough reviews and feedback, and John Piatt, for the invitation to be involved in this special issue. C.M. was supported by an Australian Government Research Training Program (RTP) Scholarship, the Holsworth Wildlife Research Endowment Fund, and the IMAS Research Committee Student Research Support Scheme. Field trip logistics were funded by the Department of Climate Change, Energy, the Environment and Water and the Department of Natural Resources and Environment Tasmania.

LITERATURE CITED

- Alderman R, Gales R, Tuck GN, Lebreton JD (2011) Global population status of shy albatross and an assessment of colony-specific trends and drivers. *Wildl Res* 38:672–686
- Alderman R, Hobday AJ (2017) Developing a climate adaptation strategy for vulnerable seabirds based on prioritisation of intervention options. *Deep Sea Res II* 140:290–297
- Andreasson F, Nilsson JÅ, Nord A (2020) Avian reproduction in a warming world. *Front Ecol Evol* 8:337
- Babcock RC, Bustamante RH, Fulton EA, Fulton DJ and others (2019) Severe continental-scale impacts of climate change are happening now: extreme climate events impact marine habitat forming communities along 45% of Australia's coast. *Front Mar Sci* 6:411
- Boyles JG, Seebacher F, Smit B, McKechnie AE (2011) Adaptive thermoregulation in endotherms may alter responses to climate change. *Integr Comp Biol* 51:676–690
- Bradburn MJ, Clark TG, Love SB, Altman DG (2003a) Survival analysis part II: multivariate data analysis—an introduction to concepts and methods. *Br J Cancer* 89:431–436
- Bradburn MJ, Clark TG, Love SB, Altman DG (2003b) Survival analysis part III: multivariate data analysis—choosing a model and assessing its adequacy and fit. *Br J Cancer* 89:605–611
- Clark TG, Bradburn MJ, Love SB, Altman DG (2003) Survival analysis part I: basic concepts and first analyses. *Br J Cancer* 89:232–238
- Cohen JM, Fink D, Zuckerberg B (2020) Avian responses to extreme weather across functional traits and temporal scales. *Glob Change Biol* 26:4240–4250
- Cook TR, Martin R, Roberts J, Häkkinen H and others (2020) Parenting in a warming world: thermoregulatory responses to heat stress in an endangered seabird. *Conserv Physiol* 8:coz109
- Cunningham SJ, Gardner JL, Martin RO (2021) Opportunity costs and the response of birds and mammals to climate warming. *Front Ecol Environ* 19:300–307
- Eastwood JR, Connallon T, Delhey K, Hall ML and others (2022) Hot and dry conditions predict shorter nestling telomeres in an endangered songbird: implications for population persistence. *Proc Natl Acad Sci USA* 119:e2122944119
- Gardner JL, Clayton M, Allen R, Stein J, Bonnet T (2022) The effects of temperature extremes on survival in two semi-arid Australian bird communities over three decades, with predictions to 2104. *Glob Ecol Biogeogr* 31:2498–2509
- Hedd A, Gales R (2005) Breeding and overwintering ecology of shy albatrosses in southern Australia: year-round patterns of colony attendance and foraging-trip durations. *Condor* 107:375–387
- Hess K (2021) muhaz: hazard function estimation in survival analysis. R ver. 1.2.6.4. <https://CRAN.R-project.org/package=muhaz>
- Hobday AJ, Pecl GT (2014) Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. *Rev Fish Biol Fish* 24:415–425
- Holt KA, Boersma PD (2022) Unprecedented heat mortality of Magellanic penguins. *Ornitholog Appl* 124:dua052
- IPCC (2021) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL and others (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 3–32, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf
- IPCC (2022) Summary for policymakers. In: Pörtner HO, Roberts DC, Poloczanska ES, Mintenbeck K and others (eds) Climate Change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 3–33
- Jacox MG, Alexander MA, Amaya D, Becker E and others (2022) Global seasonal forecasts of marine heatwaves. *Nature* 604:486–490
- Jenouvrier S, Desprez M, Fay R, Barbraud C, Weimerskirch H, Delord K, Caswell H (2018) Climate change and functional traits affect population dynamics of a long-lived seabird. *J Anim Ecol* 87:906–920
- Kaplan EL, Meier P (1958) Nonparametric estimation from incomplete observations. *J Am Stat Assoc* 53:457–481
- Lynch TP, Alderman R, Hobday AJ (2015) A high-resolution panorama camera system for monitoring colony-wide seabird nesting behaviour. *Methods Ecol Evol* 6:491–499
- Marcelino J, Silva JP, Gameiro J, Silva A, Rego FC, Moreira F, Catry I (2020) Extreme events are more likely to affect the breeding success of lesser kestrels than average climate change. *Sci Rep* 10:7207
- Mason C (2023) Shy albatross *Thalassarche cauta* conservation under climate change. PhD thesis, University of Tasmania, Hobart
- Mason C, Hobday AJ, Lea MA, Alderman R (2023) Individual consistency in the localised foraging behaviour of shy albatross (*Thalassarche cauta*). *Ecol Evol* 13:e10644
- Maxwell SL, Butt N, Maron M, McAlpine CA and others (2019) Conservation implications of ecological responses to extreme weather and climate events. *Divers Distrib* 25:613–625
- McCafferty DJ, Koprowski R, Herborn K, Tattersall GJ, Jerem P, Nord A (2021) Editorial: advances in thermal imaging. *J Therm Biol* 102:103109
- Mo M, Roache M, Davies J, Hopper J and others (2021) Esti-

- mating flying-fox mortality associated with abandonments of pups and extreme heat events during the austral summer of 2019–20. *Pac Conserv Biol* 28:124–139
- ✦ Murali G, Iwamura T, Meiri S, Roll U (2023) Future temperature extremes threaten land vertebrates. *Nature* 615: 461–467
- ✦ Neilson EW, Lamb CT, Konkolics SM, Peers MJL and others (2020) There's a storm a-coming: ecological resilience and resistance to extreme weather events. *Ecol Evol* 10: 12147–12156
- ✦ Oswald SA, Arnold JM (2012) Direct impacts of climatic warming on heat stress in endothermic species: seabirds as bioindicators of changing thermoregulatory constraints. *Integr Zool* 7:121–136
- ✦ Quintana F, Uhart MM, Gallo L, Mattera MB, Rimondi A, Gómez-Laich A (2022) Heat-related massive chick mortality in an imperial cormorant *Leucocarbo atriceps* colony from Patagonia, Argentina. *Polar Biol* 45:275–284
- R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- ✦ Ratnayake HU, Kearney MR, Govekar P, Karoly D, Welbergen JA (2019) Forecasting wildlife die-offs from extreme heat events. *Anim Conserv* 22:386–395
- ✦ Smale DA, Wernberg T, Oliver ECJ, Thomsen M and others (2019) Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat Clim Chang* 9: 306–312
- ✦ Stone DW, Gunn C, Nord A, Phillips RA, McCafferty DJ (2021) Plumage development and environmental factors influence surface temperature gradients and heat loss in wandering albatross chicks. *J Therm Biol* 97:102777
- ✦ Suryan RM, Anderson DJ, Shaffer SA, Roby DD and others (2008) Wind, waves, and wing loading: morphological specialization may limit range expansion of endangered albatrosses. *PLOS ONE* 3:e4016
- Therneau TM (2021) survival: survival analysis. R ver. 3.5.5. <https://CRAN.R-project.org/package=survival>
- Therneau TM, Grambsch PM (2000) Modeling survival data: extending the Cox model. Springer, New York, NY
- ✦ Thomson RB, Alderman RL, Tuck GN, Hobday AJ (2015) Effects of climate change and fisheries bycatch on shy albatross (*Thalassarche cauta*) in Southern Australia. *PLOS ONE* 10:e0127006
- ✦ van de Ven TMFN, McKechnie AE, Er S, Cunningham SJ (2020a) High temperatures are associated with substantial reductions in breeding success and offspring quality in an arid-zone bird. *Oecologia* 193:225–235
- ✦ van de Ven TMFN, Fuller A, Clutton-Brock TH (2020b) Effects of climate change on pup growth and survival in a cooperative mammal, the meerkat. *Funct Ecol* 34:194–202
- ✦ Welbergen JA, Klose SM, Markus N, Eby P (2008) Climate change and the effects of temperature extremes on Australian flying-foxes. *Proc R Soc B* 275:419–425
- ✦ Woodroffe R, Groom R, McNutt JW (2017) Hot dogs: high ambient temperatures impact reproductive success in a tropical carnivore. *J Anim Ecol* 86:1329–1338
- Woods R (2004) Results of a preliminary disease survey in shy albatross (*Thalassarche cauta* Gould 1841) chicks at Albatross Island. In: Annual conference of the Australian Association of Veterinary Conservation Biologists, 3 May 2004, Canberra, p 98–104, <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84936744823&partnerID=40&md5=4bafccfb0d17454ed6247584934be56e>

Editorial responsibility: Robert M. Suryan,
Juneau, Alaska, USA

Reviewed by: C. Carere and 2 anonymous referees

Submitted: November 13, 2022

Accepted: November 28, 2023

Proofs received from author(s): February 1, 2024