

Environmental Drivers of low Calf Survival in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in an Australian Marine Protected Area

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Abstract

Early-life survival is a key determinant of population dynamics in long-lived marine mammals and may be increasingly influenced by climate-driven environmental change, yet the drivers of calf mortality remain poorly understood in many coastal systems. In this study, we quantified calf survival and investigated environmental influences on early-life mortality in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) inhabiting the Adelaide Dolphin Sanctuary, South Australia. Using data collected between 2005 and 2025 on 81 recorded birth events (59 with known outcomes) from the Adelaide Dolphin Sanctuary, South Australia (34.625°S, 138.375°E), we estimated survival probabilities using Kaplan–Meier analysis, and examined the effects of marine heatwaves, storm-events, and rainfall on mortality risk using Cox proportional hazards models with time-dependent covariates.

Calf survival was low relative to other studied bottlenose dolphin populations, with only 35.6% of individuals surviving to 24 months. Mortality was highest in the neonatal period but continued to accrue over the first two years of life. Exposure to marine heatwaves showed a consistent positive association with mortality risk, though effects did not reach statistical significance, likely reflecting limited statistical power given the small size of this population. Storm-events were significantly associated with calf mortality, increasing mortality risk over the first 24 months of life (HR = 3.53, 95% CI: 1.03–12.11).

Given projected increases in marine heatwaves and storms under climate change, these findings raise concern for the population's long-term resilience and long term conservation.

Introduction

Anthropogenic climate change is driving widespread ecological change through rising temperatures and an increasing frequency and severity of extreme weather events, including heatwaves, storms, droughts, floods, and wildfires (Masson-Delmotte and Intergovernmental Panel on Climate Change. Working Group I 2023). These climatic disturbances are reshaping ecological processes across terrestrial, freshwater, and marine systems, with far-reaching consequences for species distributions, population dynamics, and ecosystem functioning (Pecl et al. 2017).

Among these disturbances, heatwaves have emerged as one of the most pronounced manifestations of contemporary climate change, increasing in frequency, intensity, and duration over recent decades (Oliver et al. 2018). Exposure to extreme temperatures can impair physiological function, alter behaviour, reduce reproductive performance, and increase mortality across a wide range of taxa (Intergovernmental Panel on Climate Change 2023; Pecl et al. 2017). In marine ecosystems, heatwaves can also cause shifts in species distributions, changes in prey abundance and quality, habitat degradation, an increased disease risk (Joyce et al. 2024), and the proliferation of harmful algal blooms that may produce toxins and contribute to mass mortality events (Gao et al. 2021; Glibert et al. 2014; Gobler 2020; Landsberg 2002).

As climate change continues to intensify thermal extremes and other severe weather events, understanding their effects on vulnerable life stages is increasingly important for predicting population persistence and resilience. Bottlenose dolphins (*Tursiops* spp.) provide an ideal system in which to investigate these relationships in coastal ecosystems. As long-lived, upper trophic-level predators, they are widely regarded as indicators of marine ecosystem health, with their health and population dynamics reflecting the cumulative effects of natural and anthropogenic stressors, as well as broader ecosystem change (Bossart 2011; Wells et al. 2004). Because reproductive success and population growth are strongly influenced by calf survival, and because calf survival is closely linked to maternal investment and environmental conditions, examining the effects of heatwaves and storm-events on calves can provide important insights into how climate change may influence the demography and long-term viability of dolphin populations.

The Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) occupies a broad range of shallow coastal and inshore habitats (Perrin, Wursig, and Thewissen 2009; Kemper et al. 2025; Würsig, Thewissen, and Kovacs 2018), with a distribution spanning the Indian and western Pacific Oceans. The species is currently listed as "Near Threatened" on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, indicating that it is close to qualifying for a threatened category or is likely to qualify in the near future (Braulik 2019).

In Australia, Indo-Pacific bottlenose dolphins can be found along much of the northern, eastern, western and southern Australian coast (Kemper et al. 2025). Within South Australia, studies have identified at least five genetically differentiated populations (Bilgmann et al. 2007; Pratt et al. 2018; Pratt et al. 2023; Möller and Beheregaray 2001), including one associated with the study area for this project (Keep et al., in review), the Adelaide Dolphin Sanctuary (ADS) (Bossley et al. 2017; Haigh et al. 2025). The ADS (Fig. 1), located within the Adelaide metropolitan region, was established by the South Australian Government in 2005 (Government of South Australia 2005) to protect the resident population of this species. The sanctuary encompasses a heterogeneous estuarine system characterised by saltmarshes, mangroves, and seagrass habitats that support a diverse range of marine species (Government of South Australia 2007, 2003). Like many coastal ecosystems adjacent to major urban centres, the ADS has experienced extensive anthropogenic modification. The area has a long history of industrial and commercial activity and includes one of South Australia's busiest working ports. It also encompasses the primary manufacturing zone for the city of Adelaide, and has been subject to multiple stressors, including industrial discharge, sewage inputs, thermal pollution from power-generation stations, vessel traffic and associated noise, stormwater runoff, and the introduction of invasive marine species (Government of South Australia 2002; Lavery et al. 2009; Lavery et al. 2008; Government of South Australia 2003). Despite its current protection, uncertainty remains regarding the health and long-term viability of the resident dolphin population with recent evidence of increasing disease prevalence, elevated morbidity and mortality, and declines in abundance (Government of South Australia 2022; Haigh et al. 2025; Kirkwood, Deveney, and Goldsworthy 2022; Tomo and Kemper 2022). Another key conservation concern for this population is the low calf survival previously documented (Cook et al., in review), which may have important implications for its long-term viability.

Reproduction in bottlenose dolphins is characterised by a slow life history strategy, prolonged maternal investment, and extended calf dependency (Wells et al. 2025; Kemper et al. 2025), with calving typically showing a seasonal peak during spring and summer in sub-tropical and temperate populations (Urian et al. 1996). Females reach sexual maturity between approximately 6 and 14 years of age (Kemper et al. 2019; Kemper, Trentin, and Tomo 2014; Mann et al. 2000), and reproduction involves a prolonged gestation period of around 12 months (Perrin, Wursig, and Thewissen 2009; Würsig, Thewissen, and Kovacs 2018). Calves are usually born singly, with inter-birth intervals commonly ranging from two to six years, most commonly around three years (Mann et al. 2000; Wells et al. 2025; Baker et al. 2018; Blasi, Bruno, and Boitani 2020), reflecting the substantial energetic demands of reproduction and calf rearing. Following birth, calves remain closely associated with their mothers for several years during which they are nutritionally and socially dependent (Gibson and Mann 2008; Rilling and Young 2014; Foster et al. 2012; Morrison et al. 2021; Parker et al. 2021; Stanton et al. 2020).

Despite this substantial maternal investment, calf survival in bottlenose dolphins is often highly variable among populations (Steiner and Bossley 2008). Estimates of early-life survival span a wide range, from approximately 67% survival in the first year of life (Henderson et al. 2014) in some populations to as high as ~ 93% in others (Cheney, Thompson, and Cordes 2019). Over longer timeframes, survival has been reported as low as 40–56% by three years of age (Henderson et al. 2014; Mann et al. 2000), while other populations exhibit comparatively higher survival, with up to ~ 83% of calves surviving to 2–3 years of age (Henderson et al. 2014).

The drivers of calf survival remain incompletely understood, particularly the differences observed among populations, but are generally considered to fall into two interacting components: intrinsic factors related to calf condition, physiological resilience, and maternal investment, and extrinsic environmental influences. These differences have important management implications, as reduced calf survival can strongly influence population dynamics, affecting abundance and ultimately constraining long-term conservation outcomes (Cheney, Thompson, and Cordes 2019).

Intrinsic factors capture variation in calf resilience and vulnerability and include genetic diversity, immune function, body condition at birth, and contaminant burdens acquired through maternal transfer and prey resources (Frère et al. 2010; Marsili et al. 2019; Noren et al. 2024; Frodello, Viale, and Marchand 2002). Together, these factors can influence physiological development and disease susceptibility, with important consequences for survival during early life.

Maternal factors, also considered intrinsic factors, are a critical component of calf survival and can vary widely among females. Maternal age and reproductive experience are known to influence the quality of care, with more experienced females generally achieving higher calf survival (Brough et al. 2016; Fruet et al. 2015; Karniski, Krzyszczyk, and Mann 2018). Nevertheless, considerable individual variation persists, likely driven by differences in maternal health, genetic make-up, body condition, and energetic state (Gómez-Campos, Borrell, and Aguilar 2011; Steiner 2012). Additional factors, including disease burden

and physiological stress, may further constrain maternal investment, with important consequences for calf survival.

Extrinsic environmental factors also play a major role in shaping calf survival and can vary substantially across space and time. In temperate systems, bottlenose dolphin calves born outside the peak breeding season may experience reduced survival due to suboptimal thermal conditions and lower prey availability (Urian et al. 1996), which can constrain energy acquisition during critical stages of development. In addition, episodic environmental events such as storms, cold spells and marine heatwaves can have pronounced effects on calf survival by altering habitat conditions.

Marine heatwaves, in particular, have been associated with ecosystem-wide disruptions, including shifts in prey distribution and biomass, and declines in foraging success, with potential cascading impacts on reproductive success and calf survival (Cavole et al. 2016; Hansen 2009; Tang, Xie, and Chen 2012; Wild et al. 2019; Yeates and Houser 2008). Other external stressors, such as pollutant discharge and mobilisation, freshwater runoff and nutrient loading, as well as harmful algal blooms (HABs), may further compromise calf health through direct toxicity or indirect effects on prey resources (DeLong, Gilmartin, and Simpson 1973; Desforages et al. 2016; Dwight et al. 2002; Souter, Lettoof, et al. 2026; Tregenza et al. 2016). Finally, increasing human pressures, including recreational boating, tourism, and commercial activities, can disturb mother–calf pairs, disrupt behaviour, and elevate stress levels, potentially reducing the effectiveness of maternal care and further influencing survival outcomes (Steckenreuter, Möller, and Harcourt 2012).

Given the highly variable and multifactorial nature of calf survival, and its central role in shaping population resilience, understanding the drivers of early-life outcomes remains a key conservation priority. This is particularly relevant for coastal bottlenose dolphin populations, where demographic parameters can be strongly influenced by local environmental conditions and anthropogenic pressures. In this study, we aimed to quantify calf survival within the ADS population and examine the factors influencing early-life outcomes. Specifically, we investigated the potential role of environmental variability, including exposure to marine heatwaves, storm-events, and rainfall, as key drivers that may shape survival patterns during critical developmental stages. Based on previous evidence linking environmental variability to cetacean demographic performance, we predicted that increased exposure to marine heatwaves, storm-events, and high-rainfall periods would be associated with lower calf survival.

Materials and methods

The study area is managed by the South Australian Government under state legislation, and since its establishment in 2005, systematic monitoring has been undertaken to document key demographic events. These include calf births, mortality events, strandings (both live and deceased), and observations of injuries or health conditions recorded during field activities.

When carcasses were recovered, post-mortem examinations were generally conducted to determine causes of death and assess overall condition. From 2005 until 2020, necropsies were primarily undertaken by the South Australian Museum, while more recent cases (2022–2025) have been examined by the veterinary pathology services at the University of Adelaide through a team dedicated to dolphin research (Souter, Chaber, et al. 2026; Souter, Lettoof, et al. 2026). These assessments provided additional confirmation about mortality events and contributed to the broader demographic dataset.

Records from the Department for Environmental and Water in South Australia were used as the primary data source for this study through a data sharing agreement and draw on documented birth and mortality events within the population. Births were recorded based on the first observation or reported sighting of a calf. The analysis was restricted to calves born to females that could be reliably identified based on distinctive natural markings and were therefore monitored consistently over time. This ensured that maternal identity and reproductive histories could be confidently assigned.

When available, the month and year in which each calf was last observed were recorded. In cases where a calf was found dead in close proximity to its mother, or when a recovered carcass could be confidently matched to a known individual based on the markings, the date of death was used as the final sighting. However, because some calves may attain independence before developing stable and recognisable identifying features, individuals may have gone undetected despite surviving beyond their last recorded sighting. To minimise the risk of misclassification, analyses were therefore restricted to survival outcomes within the first 24 months of life.

Monthly sea surface temperature (SST), SST anomaly, and marine heatwave (MHW) data from January 2005 until December 2025 were obtained from the Ocean Data Bank (ODB) Marine Heatwaves portal (Institute of Oceanography, National Taiwan University accessed February 2026), which provides globally gridded fields at $0.25^\circ \times 0.25^\circ$ resolution. Data were extracted for the central coordinates of the Adelaide Dolphin Sanctuary (138.375°E , -34.625°S). The processing workflow applies a standardised procedure in which monthly MHW occurrence is derived directly from Optimum Interpolation Sea Surface Temperature (OISST) fields, using monthly averaged SST and computing anomalies relative to a fixed 1982–2011 climatological model (Jacox et al. 2020). MHW are determined when SST rose above a seasonally varying 90th-percentile threshold (Hobday et al. 2018). To evaluate how thermal variability influences dolphin early-life survival, MHW exposure was quantified for each calf as heatwave frequency, measured as the number of months during the calf's exposure period in which MHW conditions occurred. Monthly MHW occurrence was recorded as a binary variable, with months experiencing one or more heatwave events assigned a value of 1 and months with no MHW events assigned a value of 0; these values were then summed across the exposure period to calculate MHW frequency.

To identify extreme temperature anomalies, monthly SST values were detrended using a LOESS smoother fitted to the 20-year time series, and residuals were calculated as the deviation of each monthly SST from this long-term trend. The distribution of these residuals was then used to derive extreme anomaly thresholds, defined as the 90th and 10th percentiles of the residual distribution,

representing unusually warm and unusually cold conditions, respectively. These anomaly thresholds were converted to absolute SST values by adding them to the long-term trend, yielding a site-specific extreme temperature threshold of $\geq 22.5^{\circ}\text{C}$ for extreme hot events. Monthly occurrence of extreme hot conditions was then coded as a binary variable (1 = extreme hot month, 0 = otherwise) and summed across each calf's exposure period.

Monthly rainfall data for the study area were obtained from the Bureau of Meteorology (BoM) weather station at Parafield Airport, located approximately 15 km from the study site. This station was selected as the nearest long-term monitoring location with continuous and reliable records to the ADS study site. Monthly total rainfall over the past 20 years was extracted from archived climate summaries to ensure consistent temporal coverage and data quality.

Two rainfall metrics were considered: (1) total monthly rainfall and (2) the occurrence of wet months (extreme rainfall events). Total monthly rainfall was retained as a continuous measure of rainfall variability. Wet months were defined as months in which total rainfall exceeded the 90th percentile of the monthly rainfall distribution ($73.12 \text{ mm month}^{-1}$). Occurrence of wet months was coded as a binary variable (1 = wet month, 0 = otherwise), and the number of wet months experienced during each calf's exposure period was calculated.

Storm-event data for the study area were obtained from the Bureau of Meteorology (BoM), which provides records of documented severe weather occurrences. Storm-events were defined as conditions producing large hail ($> 2 \text{ cm}$), damaging or destructive wind gusts ($\geq 90 \text{ km h}^{-1}$), heavy rainfall associated with flash flooding, or tornadoes. For each month, the occurrence of at least one storm-event was recorded as a binary variable, such that months with one or more events were assigned a value of 1, and months with no recorded events were assigned a value of 0.

Environmental exposure was then quantified using five metrics: (1) MHW, (2) hot months, (3) cumulative rainfall, (4) wet months and (5) storm-events. For each calf, monthly environmental data were aligned with individual life-history records to ensure that conditions experienced corresponded to each stage of development analysed.

To assess how environmental variability influences calf survival, exposure was calculated at 24 months. Although longer-term effects may be present, analyses beyond 24 months were not conducted. This is because some calves begin to disperse from their mothers as early as two years of age and frequently lack distinctive markings required for reliable identification. Consequently, extending analyses beyond this period could bias results toward individuals that remain observable and in close proximity to their mothers.

Calves with unknown survival outcomes were excluded. For all remaining calves, the month and year of first sighting defined the start of the exposure period. The end of the window was determined by the month of death (for calves that died before the end of the window) or by truncating exposure at exactly 24 months after first sighting (for calves that survived beyond that age). This approach ensured that all

calves were evaluated over consistent and biologically meaningful periods. Monthly exposure intervals were generated for each calf and matched to the corresponding environmental values for each month within the defined window.

Statistical analysis

We assessed calf survival using Kaplan–Meier time-to-event analysis, which accommodates right-censoring (Jager et al. 2008). For each calf, we calculated the number of months between first and last sighting and estimated survival probabilities at 24 months for the full dataset. Deaths occurring within the time window were coded as events (event = 1), whereas calves that survived beyond the window were treated as censored (event = 0).

To evaluate the influence of environmental conditions on calf survival, we used Cox proportional hazards models incorporating time-dependent covariates. This approach models survival as a function of time-to-event (i.e., time until death) while accounting for variation in the environmental exposure experienced by individuals throughout early life. Unlike simpler modelling frameworks (e.g., logistic regression or generalised linear models), which treat survival as a fixed binary outcome, Cox models make use of the full temporal structure of the data and are therefore better suited for analysing survival processes in which both risk and environmental exposure vary over time (Therneau and Grambsch 2000; Abd ElHafeez et al. 2021).

Environmental covariates were updated at monthly intervals throughout each calf's observation period. Because calf age and environmental exposures were recorded at monthly resolution, tied event times were possible and were handled using Efron's approximation (Therneau and Grambsch 2000). The proportional hazards assumption was assessed using tests based on Schoenfeld residuals (Grambsch and Therneau 1994). As some females contributed multiple calves to the dataset, the potential influence of non-independence among offspring from the same mother was evaluated using models with robust standard errors clustered by maternal identity.

Environmental exposure was quantified using marine heatwaves, hot months, rainfall, wet months, and storm-events. Each variable was modelled as a time-dependent covariate, allowing exposure to vary monthly throughout each calf's observation period and accounting for temporal variation in environmental conditions experienced by individual calves. Separate Cox proportional hazards models were fitted for each environmental variable. A univariable modelling approach was adopted because the limited number of mortality events increased the risk of over-parameterisation and reduced the reliability of more complex multivariable models containing multiple, potentially correlated environmental predictors.

All analyses were conducted in RStudio (version 2026.25.0 + 218) using R (version 4.6.1). Data manipulation was performed using the *dplyr*, *tidyr*, and *lubridate* packages, while survival analyses were conducted using the *survival* and *ggsurvfit* packages. The proportional hazards assumption was assessed using Schoenfeld residual-based tests implemented in the `cox.zph()` function of the *survival*

package. Figures were generated using *ggplot2*, with support from the *scales* and *mgcv* packages where required.

Results

A total of 81 birth events from 29 identified females were recorded during the study period. Females contributed between one and eight calves each (mean = 2.8 calves per female; median = 3). Twenty-two calves had unknown 24-month outcomes, leaving 59 calves with known outcomes available for survival probability analyses. 76.5% of calves (62/81) were born between December and March (Fig. 2).

Of the 59 calves with known 24-month outcomes, 21 survived to 24 months of age and 38 died before reaching 24 months. Survival probability to 24 months was 35.6% (95% CI: 23.6–49.1%). Inspection of the 24-month Kaplan-Meier survival curve (Fig. 3) shows a sharp initial decline during the first weeks of life, with more than 25% of calves dying before reaching one month of age. Beyond this early high-risk period, the curve displays a steady, progressive reduction in survival probability across the remainder of the first two years of life. Survival decreases in smaller but consistent steps, indicating that mortality continues to accumulate rather than plateau. The gradual downward trajectory implies that later-stage mortality is not driven by a single acute event but instead reflects ongoing or cumulative pressures acting throughout the calves' early development.

Examination of annual variation in 24-month calf survival (Fig. 4), suggested a decline in survival over the study period, with lower survival observed in more recent years. However, logistic regression analysis found no statistically significant effect of year on 24-month survival ($\beta = -0.0839$, $p = 0.113$). Although this result did not reach statistical significance, the estimated effect size corresponds to an approximate 8% decline in the odds of survival per year. The confidence intervals associated with this estimate were relatively wide, likely reflecting the small number of calves contributing data in individual years, and suggesting that the study may have lacked sufficient statistical power to detect a modest temporal trend in survival.

Calf survival

Several females contributed multiple calves to the dataset, with individual females producing between one and eight calves over the study period. To evaluate the potential influence of non-independence among offspring from the same mother, model inferences were compared with analyses incorporating robust standard errors clustered by maternal identity. Accounting for maternal clustering did not alter the magnitude or direction of the observed effects, indicating that the results were robust to repeated offspring from the same female.

Prior to interpreting the Cox proportional hazards models, the proportional hazards assumption was evaluated for each environmental variable using Schoenfeld residual tests. The Cox model assumes that the effect of a predictor on mortality risk remains proportional through time and therefore a covariate

associated with an increase or decrease in mortality risk is assumed to have a consistent effect throughout the observation period. Violation of this assumption suggests that the effect of a predictor changes over time and therefore cannot be adequately described by a single hazard ratio.

Tests of the proportional hazards assumption indicated no evidence of violation for the marine heatwave model ($\chi^2 = 0.203, p = 0.65$), storm-event model ($\chi^2 = 0.693, p = 0.41$), or the wet-month model ($\chi^2 = 3.58, p = 0.059$). In contrast, the assumption was violated for the hot-month model ($\chi^2 = 7.94, p = 0.0048$) and rainfall model ($\chi^2 = 6.10, p = 0.013$), indicating that the effects of these variables varied through time. Consequently, subsequent interpretation focused primarily on the marine heatwave, storm-event, and wet-month models, for which the proportional hazards assumption was adequately satisfied.

Among the environmental variables that satisfied the proportional hazards assumption, the occurrence of wet months showed no association with calf survival over the first 24 months of life ($\beta = 0.04 \pm 0.64$ SE, $z = 0.06, p = 0.954$). The estimated hazard ratio was close to one, indicating no measurable effect of extreme rainfall events on mortality risk (Fig. 4).

Exposure to marine heatwaves was positively associated with calf mortality risk over the 24-month observation period ($\beta = 0.57 \pm 0.35$ SE, $z = 1.65, p = 0.099$; HR = 1.78) (Fig. 4). Although this relationship did not reach conventional levels of statistical significance, the magnitude of the estimated effect suggests that calves exposed to marine heatwaves experienced an approximately 78% higher mortality hazard than those not exposed. Confidence intervals around the estimate were relatively wide, indicating substantial uncertainty in the effect size. Given the small size of the study population and the limited number of mortality events available for analysis, the ability to detect moderate effects was constrained.

Storm-event exposure was significantly associated with increased mortality risk ($\beta = 1.26 \pm 0.63$ SE, $z = 2.00, p = 0.045$; HR = 3.53, 95% CI: 1.03–12.11) (Fig. 5). This result indicates that mortality hazard was approximately 3.5 times higher during months in which storm-events occurred compared with months without storm-events. Together, these findings indicate that storm-events showed the strongest association with calf mortality among the environmental variables considered, while exposure to marine heatwaves was also associated with increased mortality risk.

Descriptive mortality rates showed that mortality during marine heatwave months was 7.59 deaths per 100 calf-months compared with 4.58 deaths per 100 calf-months during non-heatwave months. Similarly, mortality during storm-event months was 9.09 deaths per 100 calf-months compared with 5.45 deaths per 100 calf-months during months without storm-events (Fig. 6)

Discussion / Conclusion

This study highlights that low calf survival is a key determinant of population dynamics in this system, with calf survival probabilities well below those reported for other bottlenose dolphin populations. Previous studies have documented first-year survival ranging from 67% to more than 90%, and survival to two or three years between 40% and 83% (Henderson et al. 2014; Mann et al. 2000; Robinson et al. 2017;

Steiner and Bossley 2008). In contrast, the low survival observed here (35.6% at 24 months) suggests that early-life stages represent a critical bottleneck for population persistence.

Findings from the limited number of necropsied calves suggest that a range of conditions may have contributed to mortality, including poor nutritional status, lesions consistent with infectious disease, congenital abnormalities, and/or contaminant exposure (Adamczak, Kemper, and Tomo 2018; Government of South Australia 2022; Newman et al. 2025; Tomo and Kemper 2022; Souter, Chaber, et al. 2026). In addition, reduced genetic diversity and elevated levels of individual inbreeding have been documented within the population (Keep et al., in review), potentially increasing susceptibility to environmental and health-related stressors. Together, these findings suggest that mortality may result from the cumulative effects of multiple pressures rather than a single causal mechanism. However, the low rate of calf carcass retrieval limits the ability to determine the relative contribution of these factors to observed mortality patterns. This lack of diagnostic information constrains understanding of the mechanisms underlying calf loss and highlights the importance of improving carcass recovery and post-mortem investigations. Improved recovery of fresh carcasses followed by comprehensive necropsy, histopathology, microbiology, toxicology, genetic and ancillary diagnostic testing would substantially improve understanding of the pathological processes underlying calf mortality.

The observed relationship between MHW exposure and calf survival, together with the significant effects of storm-events, adds to growing evidence that thermal stress (Wild et al. 2019; Hansen 2009; Tang, Xie, and Chen 2012; Yeates and Houser 2008) and extreme weather conditions can be important drivers of early-life mortality in dolphins. Elevated temperatures and severe storm-events may increase physiological and energetic demands, disrupt foraging opportunities, and reduce prey availability during a life stage that is highly vulnerable. These findings are particularly concerning given projected increases in the frequency, duration, and intensity of marine heatwaves, elevated sea-surface temperatures, and extreme weather events under continued climate change (Oliver et al. 2019; Roberts et al. 2019; Sanderson and Alexander 2020; Wernberg et al. 2016). Consequently, calves in the ADS are likely to experience increasingly variable and thermally challenging environmental conditions, potentially exacerbating energetic stress and further reducing survival during early life.

The implications of these findings are directly relevant for the management of the ADS dolphin population and others living in urban environments. In addition to broad-scale climate drivers, localised anthropogenic heat sources, such as warm water discharges from power stations, may further elevate thermal conditions within critical habitats. Reducing additional thermal inputs where possible could therefore represent a practical management action to mitigate cumulative thermal stress. More broadly, ongoing monitoring of temperature regimes, storm activity, and habitat quality should be prioritised to support proactive, climate-informed management strategies aimed at improving calf survival.

Similar climate-informed monitoring approaches are increasingly being implemented elsewhere. Long-term monitoring programs on inshore dolphin populations such as in Sarasota Bay, Florida, have integrated assessments of population demographics, health, environmental conditions and prey

resources to identify emerging threats and guide management actions (Wells et al. 2025). In the Indian River Lagoon, also in Florida, mortality investigations have been coupled with ecosystem monitoring, including assessments of water quality, seagrass loss and prey availability following large-scale ecological disturbances (Stolen et al. 2025). Such integrated frameworks provide valuable examples for the ADS, where linking environmental indicators with demographic and health data could improve the early detection of emerging risks and inform adaptive management responses.

Future research should also consider the potential role of harmful algal blooms (HABs) in shaping dolphin health and survival. HAB events can cause direct mortality in marine fauna through toxin exposure (Broadwater et al. 2018; Fire et al. 2007; Jensen et al. 2015; Landsberg et al. 2005; Landsberg 2002) and may also indirectly affect dolphins by altering prey communities, reducing prey availability, and degrading habitat quality. In several coastal ecosystems, HABs have been linked to unusual mortality events and broader ecosystem disruptions (Landsberg 2002; Leandro et al. 2010; Lefebvre et al. 1999; McHugh et al. 2011; Murray et al. 2025). Given the increasing occurrence of HABs globally (Gobler 2020) and the potential influence of warming waters on bloom dynamics, understanding their role within the ADS ecosystem should be considered a priority for future monitoring efforts.

Of the 10 calves born between 2018 and 2020, only one survived to 24 months of age. This low level of calf survival began before and continued through the onset of the 2020–2021 unusual mortality event (Government of South Australia 2022), which affected mainly juvenile and subadult male dolphins, and subsequently triggered a multidisciplinary investigation into potential underlying causes. While these events may reflect unrelated processes, they may have had compounding impacts on the population. These events unfolded against the broader backdrop of long-term population dynamics: an increase in abundance from 1993 to the early 2000s, a period of relative stability between 2003 and 2016 when estimates remained comparatively high, and a subsequent decline to levels similar to those recorded in the early 2000s (Bossley et al. 2017; Haigh et al. 2025). The temporal overlap between elevated calf mortality, declining abundance estimates and subsequent unusual mortality events suggests that demographic and health-related processes may be interacting to influence population trajectories. While causal relationships cannot be established from the available data, sustained reductions in calf recruitment are expected to have long-term consequences for population viability, particularly in small, resident populations where opportunities for immigration are limited.

This study identifies low calf survival as a key demographic bottleneck influencing the long-term persistence of the ADS bottlenose dolphin population. Survival probability to 24 months was substantially lower than that reported for many other bottlenose dolphin populations, highlighting the importance of understanding the factors influencing early-life mortality. Our findings indicate that storm-events were associated with increased calf mortality risk, while marine heatwaves may also have contributed to reduced survival. These results suggest that environmental conditions play an important role in shaping reproductive success and population dynamics, and that climate-related stressors may represent an increasing challenge for the persistence of inshore dolphin populations into the future.

The study also highlights the value of integrating demographic, environmental, and health-based datasets to better understand dolphin population trajectories and identify the mechanisms underlying calf mortality. Improved monitoring of individual health, enhanced carcass recovery and necropsy investigations, contaminant assessments, and ecosystem monitoring will be critical for advancing this understanding. Collectively, these findings identify dolphin early-life mortality as a priority conservation concern and emphasise the need for proactive, climate-informed management strategies aimed at improving calf survival, enhancing population resilience, and supporting the long-term persistence of this small urban dolphin population.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval

This study was based on long-term observational and photo-identification research of wild Indo-Pacific bottlenose dolphins (*Tursiops aduncus*). All research activities were conducted in accordance with applicable international, national, and institutional guidelines for the study of wild animals and were undertaken under the relevant permits and approvals issued by the appropriate authorities.

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Author Contribution

All authors contributed to the conception and design of the study, with the initial conceptual framework developed by Cristina Vicente-Sánchez, Guido J. Parra, and Luciana M. Möller. Data collection and management were undertaken by the South Australian Department for Environment and Water (DEW). The Department provided approval for the use of these data in this research. Data curation was performed by Cristina Vicente-Sánchez with support from Nikki Zanardo. Statistical analyses were conducted by Cristina Vicente-Sánchez and Simon Wotherspoon. Information on necropsied animals and broader ecological and historical knowledge of the study population and study area were provided by Catherine M. Kemper and Ikuko Tomo. The first draft of the manuscript was written by Cristina Vicente-Sánchez. All authors contributed to the interpretation of results, reviewed and commented on previous versions of the manuscript, and approved the final manuscript.

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Data Availability

The datasets analysed during the current study are not publicly available because they were provided by the Department for Environment and Water, South Australia, under a data-sharing agreement. Data may be available from the Department for Environment and Water subject to approval and applicable data access conditions.

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Figures

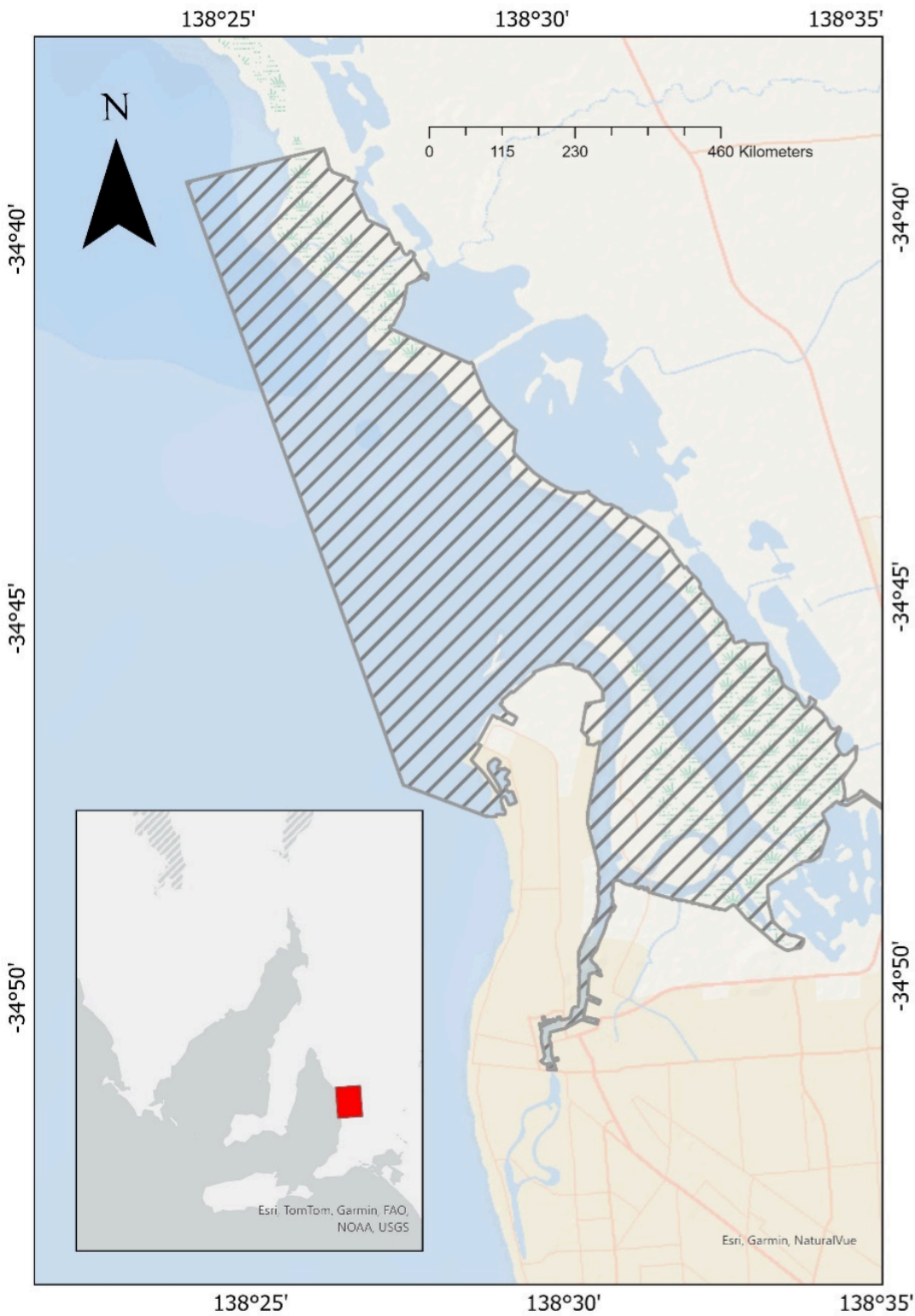


Figure 1

Location of the study area in South Australia (left) and a detailed view of the study area boundaries (dashed outline) within the Adelaide Dolphin Sanctuary, Gulf St Vincent, South Australia.

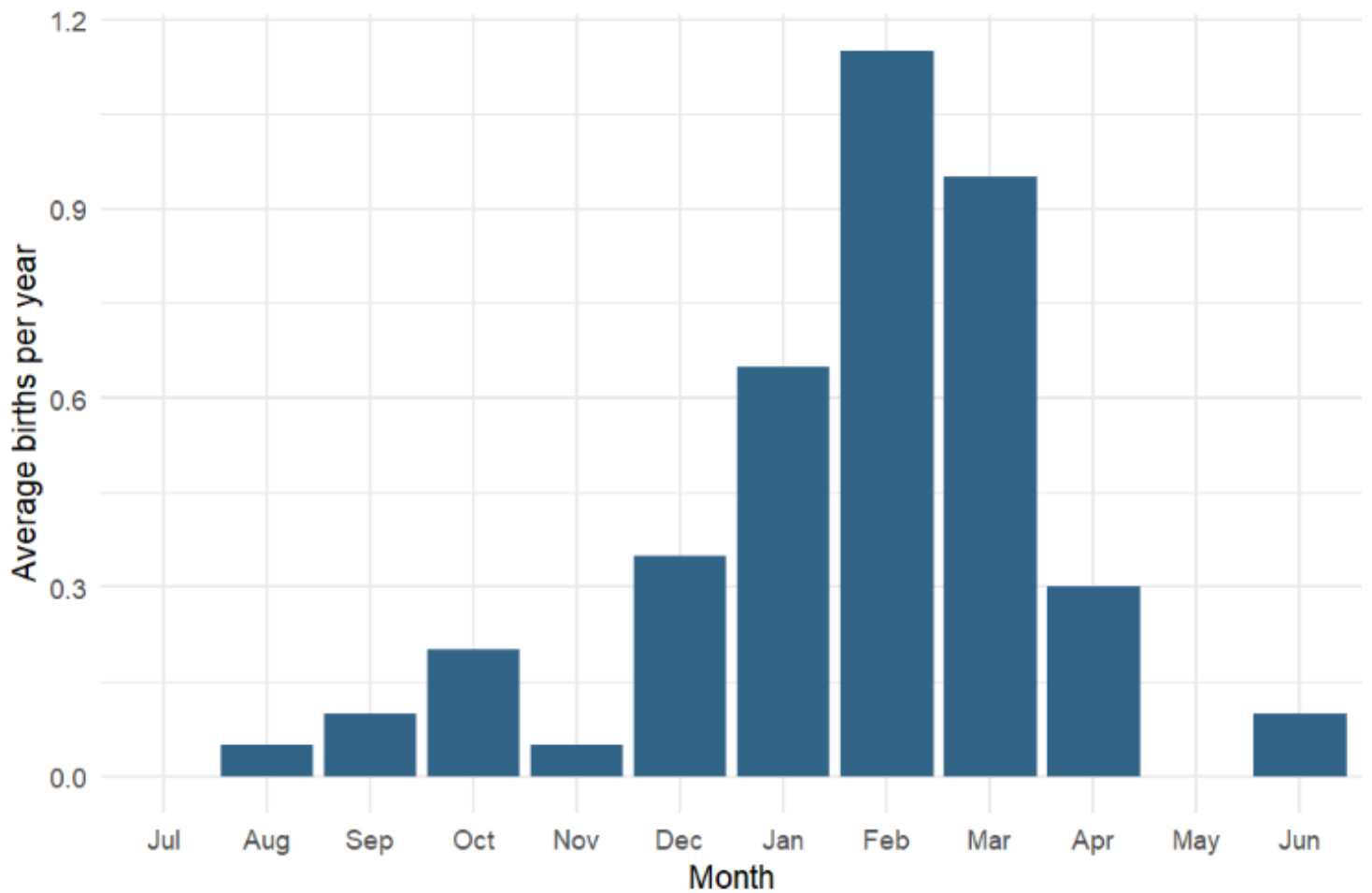


Figure 2

Monthly average of calf births for Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in the Adelaide Dolphin Sanctuary, South Australia, between 2005 and 2025.

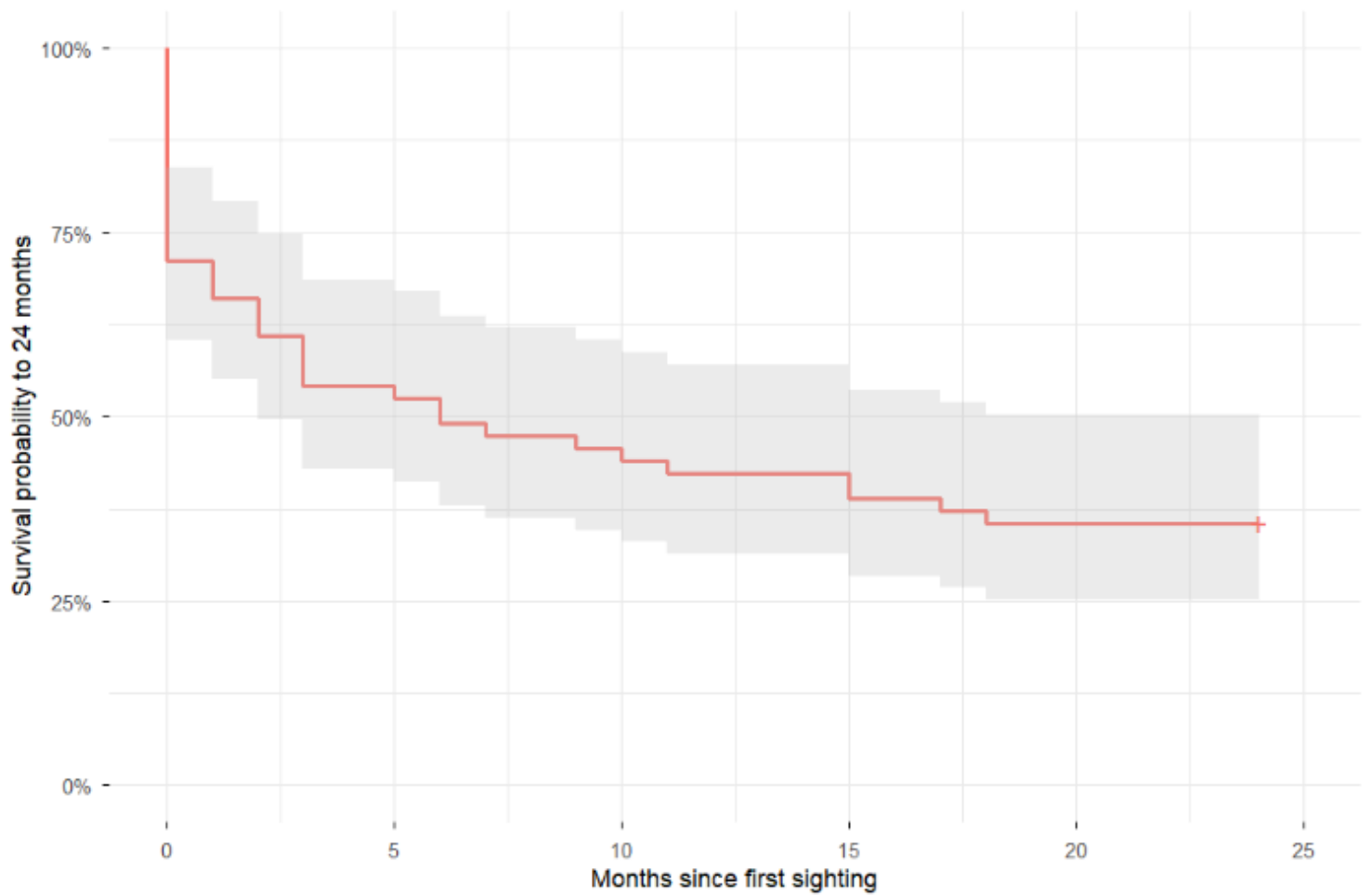


Figure 3

Kaplan–Meier survival curves showing the probability of calf survival to 24 months for Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) of the Adelaide Dolphin Sanctuary, South Australia. Shaded areas represent 95% confidence intervals. Survival declined most sharply during the first month of a dolphin’s life.

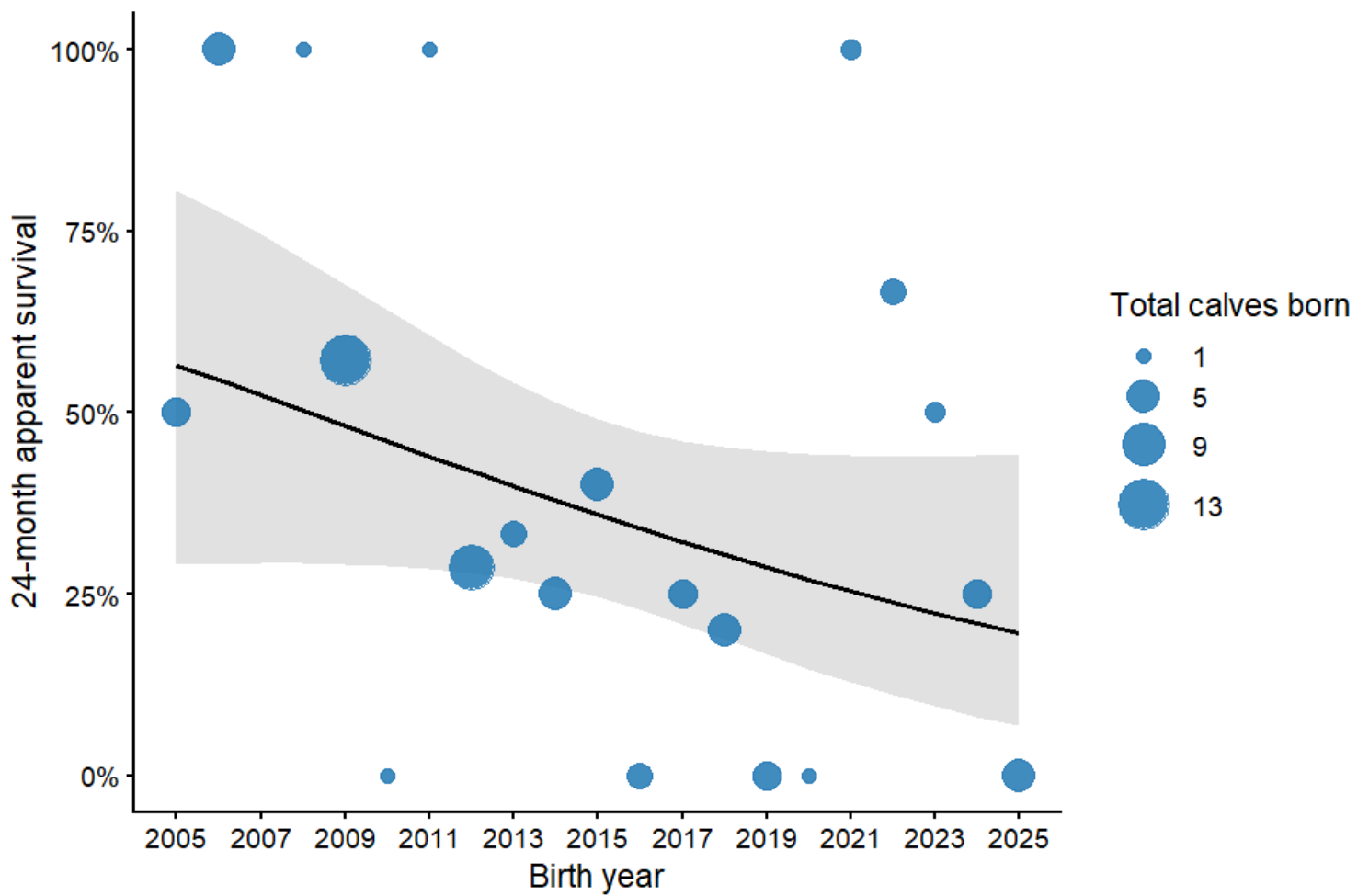


Figure 4

Temporal variation in 24-month apparent survival of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in the Adelaide Dolphin Sanctuary, South Australia. Points show annual calf survival estimates by birth year, with point size proportional to the total number of calves born. The solid line represents the fitted binomial logistic regression trend and the shaded area the 95% confidence interval.

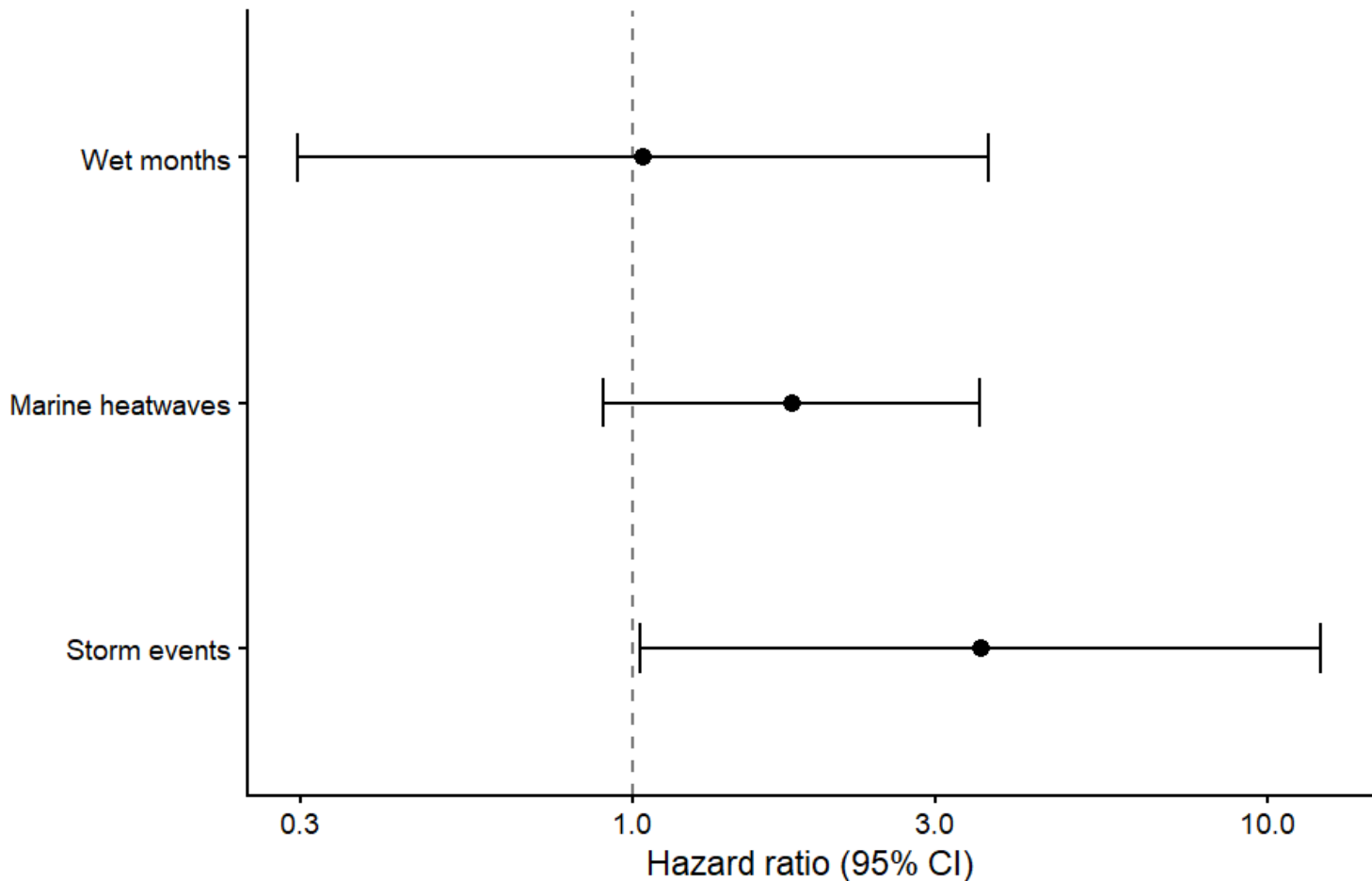


Figure 5

Hazard ratios (points) with 95% confidence intervals (horizontal bars) for the effect of monthly wet-month, marine heatwave and storm-event exposure on calf mortality during the first 24 months of life in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) of the Adelaide Dolphin Sanctuary, South Australia. Values above 1 indicate elevated mortality risk during months in which the condition occurred, relative to months without it; the dashed vertical line indicates a hazard ratio of 1 (no difference in mortality risk).

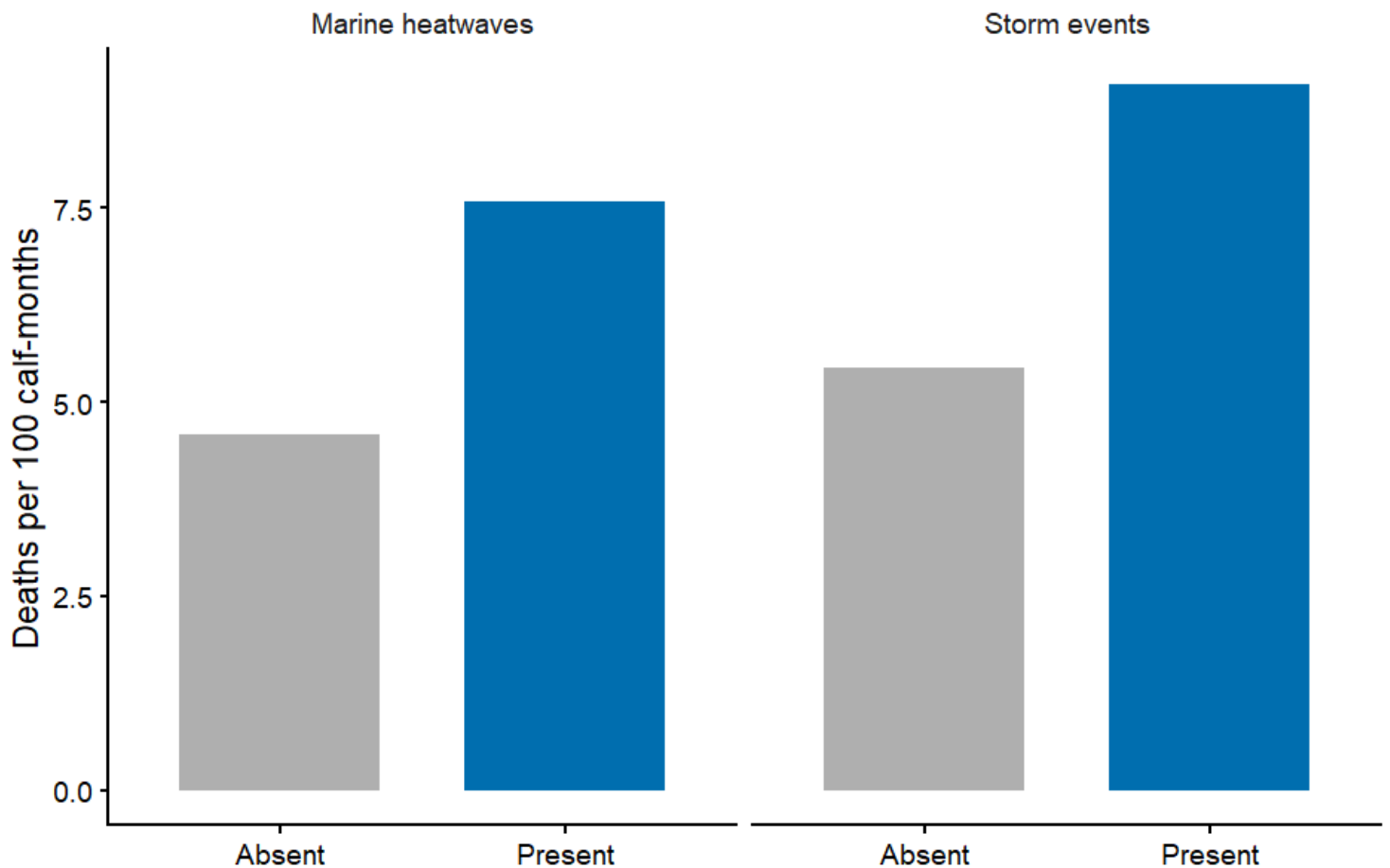


Figure 6

Observed calf mortality rates life in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) of the Adelaide Dolphin Sanctuary, during months with and without marine heatwaves and storm-events. Values represent the number of deaths per 100 calf-months of observation. Mortality rates were higher during months in which marine heatwaves or storm-events occurred than during months without these environmental conditions.