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Seasonal Prevalence of Skin Lesions on Dolphins across a Natural Salinity Gradient

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Abstract: Bottlenose dolphins (*Tursiops truncatus*) inhabit waters across a broad natural salinity gradient and exhibit changes in skin condition based on the quality of their environment. Prolonged exposure to low salinities (≤10–20 ppt) degenerates the epidermal barrier and causes cutaneous lesions in dolphins, while the role of high salinity exposure (>35 ppt) in lesion development remains unknown. We assessed seasonal lesion prevalence in three free-ranging dolphin stocks inhabiting coastal Gulf of Mexico (GoM) waters of different salinities (0–30 ppt, 22–35 ppt, and 36+ ppt) using images of dolphin bodies. Lesions were documented on 44% of the dolphins photographed (n = 432), and lesion occurrence was significantly related to cold seasons and water temperatures but not salinity. Cold water temperatures may heighten dolphin susceptibility to infectious pathogens and disease and compound the effects of anthropogenic pollutants in the GoM. As dolphins are a bioindicator species of marine habitat welfare, natural studies assessing dolphin skin may reveal environmental degradation with potential impacts on marine ecosystems and human health.

Keywords: bioindicator; bottlenose dolphin; epidermal disease; Gulf of Mexico; hypersaline

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1. Introduction

Bottlenose dolphins (*Tursiops truncatus*; hereafter "dolphins") residing in bays, sounds, and estuaries of the Gulf of Mexico (GoM) can experience physiological changes resulting from exposure to a broad range of natural salinities [1–3]. The salinity gradient of the coastal GoM is driven by fluctuations in global precipitation and the hydrological cycle, which are often intensified by anthropogenic stressors [4,5]. Free-ranging dolphins generally live in marine waters with an average salinity of 35 parts per thousand (ppt), although some dolphins utilize lower salinity habitats (e.g., <20 ppt) [6]. Skin disorders (hereafter "lesions") in dolphins are commonly associated with low salinity exposure, which increases the permeability of dolphin skin and fluid accumulation in the superficial epithelial layer [1]. Dolphins that frequently utilize low salinity habitats may be physiologically adapted to local salinity fluctuations or may use stratified water columns with higher salinities at depth [7]. Dolphins can also inhabit hypersaline lagoons (≥36 ppt) where salinities can double that of the GoM [8], although site fidelity in these hypersaline systems is poorly understood and the effects of hypersaline exposure on lesion development have not been assessed.

Lesions on dolphins can be highly variable in origin and manifestation and are often context-dependent. Exposure to salinities < 10 ppt (often resulting from tropical storms and freshwater inundation in shallow systems) for several days or weeks generally induces skin pallor and cutaneous lesions in dolphins of varying degenerative stages [6,9]. Despite the continuous sloughing (i.e., shedding) of dolphin skin, fungi, algae, and bacteria may penetrate the epidermal barrier as integrity decreases [6]. Once the skin barrier is compromised, a dolphin risks secondary infection, freshwater influx into the body, and subsequent electrolyte imbalance, including disruption of internal sodium and water homeostasis [6,10]. Lesions on dolphins may be seasonally prominent and linked to periods of physiological stress [11,12]. For instance, low water temperatures may pose thermal constraints on dolphins and limit blood flow to the skin, reducing immune protection and increasing lesion manifestation [11,13,14]. Since coastal dolphins in the GoM inhabit ecosystems subject to seasonal variations in salinity and water temperature, lesion prevalence may fluctuate with natural shifts in the environment [10]. Physiological complications associated with lesions can be exacerbated by exposure to polluted waters, as contaminants can bioaccumulate to toxic levels and intensify lesion development and comorbidities [13,15]. Suppression of immune function and/or persisting epidermal lesions may further expose dolphins to physiological stress and lesion outbreaks [16–19].

As epidermal lesions can manifest from both natural and anthropogenic disturbances, variability in the integrity of dolphin skin may reflect large-scale shifts in environmental quality [6,20,21]. Coastal dolphins are often long-term residents of confined bay systems where anthropogenic pressures may be prominent. Dolphins can be useful indicators of ecosystem health and important informants of potential health risks to humans from fish and seafood consumption [20,22,23]. Dolphins are also abundant in port areas inundated with vessel traffic, dredging, and piling activities that reduce habitat quality and introduce chemical pollutants through sediment suspension [24,25]. With climate change intensifying globally, extreme alterations in salinity, water temperature, and the atmosphere provide fertile conditions for the development of pathogenic disease and viral outbreaks, subjecting both marine and human populations to exposure through biomagnification in the food web [26]. There is a crucial need to understand how lesion development in dolphins varies with environmental quality, particularly in areas where anthropogenic disturbance is high, to develop more sustainable practices and preserve marine communities that are highly susceptible.

Photographs of dorsal fins are commonly used to estimate lesion prevalence (i.e., percentage of a population or stock with lesions) among free-ranging dolphins when it is difficult to photograph large proportions of dolphin bodies [27,28]. The dorsal fin is the most routinely visible feature of a dolphin at the surface and can be used to identify unique individuals across time, space, and populations [29], aiding in the standardization of lesion assessment. However, using dorsal fins as a proxy often underestimates the extent and expression of lesions on the whole body [27,28], limiting our knowledge of lesion prevalence in free-ranging populations. Since most lesion cases have unknown etiologies and are challenging to distinguish categorically, measurements of lesion prevalence are recommended [28,30].

Our objective was to assess the seasonal prevalence (percentage) of epidermal lesions on the bodies of free-ranging bottlenose dolphins inhabiting mesohaline (5–18 ppt), polyhaline (18–30 ppt), and hypersaline ($\geq$36 ppt) waters. We examined dolphins along the coastal Texas and Mississippi regions of the northwestern GoM, including Redfish Bay (RB), Texas, Upper Laguna Madre (ULM), Texas, and Mississippi Sound (MS), Mississippi. RB is a shallow system that experiences seasonal changes in water temperature (15–30 °C) and salinity (22–35 ppt) [31]. RB is adjacent to the Port of Corpus Christi, the largest U.S. port in total revenue tonnage [32], with boats proximate to dolphins 80% of the time [33]. Channel dredging to accommodate increased vessel traffic has been ongoing since 1857, and growing mineral production activities in the past decade surrounding RB are of concern for local water quality and biota health [31]. ULM is one of six naturally occurring coastal hypersaline lagoons in the world [8,34] where salinities regularly exceed 45 ppt (average 36 ppt) due to low circulation and little freshwater inflow [35,36]. MS experiences large fluctuations in sea surface temperature (9–33 °C) and salinity (0–30 ppt) due to intense freshwater river discharges (Mississippi, Pearl, Pascagoula, and Mobile Rivers) and frequent tropical weather [37]. All three dolphin stocks are considered highly vulnerable to climate change and a high management priority by the National Oceanic and Atmospheric Administration (NOAA) [38].

Lesion prevalence in dolphin stocks was assessed relative to salinity, water temperature, and season. We hypothesized that dolphins in high salinities would have a lower prevalence of skin lesions [39] and that cooler water temperatures in the fall and winter would increase lesion prevalence [11]. By assessing the epidermal condition of dolphins exposed to a large salinity gradient, it is possible to begin filling data gaps for populations set as high management priorities by the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA NMFS) and to proactively monitor the health and sustainability of marine species and ecosystems where salinity is highly variable.

2. Materials and Methods

Photographs of the dorsal fins and the visible bodies of dolphins were collected opportunistically during boat-based surveys for distinct dolphin stocks inhabiting RB (2012–2014, 2022), ULM (2022), and MS (2013; Figure 1). Images collected between 2012 and 2014 in RB and MS were obtained from survey efforts conducted by the NOAA Southeast Fisheries Science Center Marine Mammal and Turtle Division. All survey efforts were performed under NOAA NMFS permits 21,938, 779–1633, and 14,450, and Texas A&M University-Corpus Christi's Institutional Animal Care and Use Committee (IACUC) permit 2021-10-031.

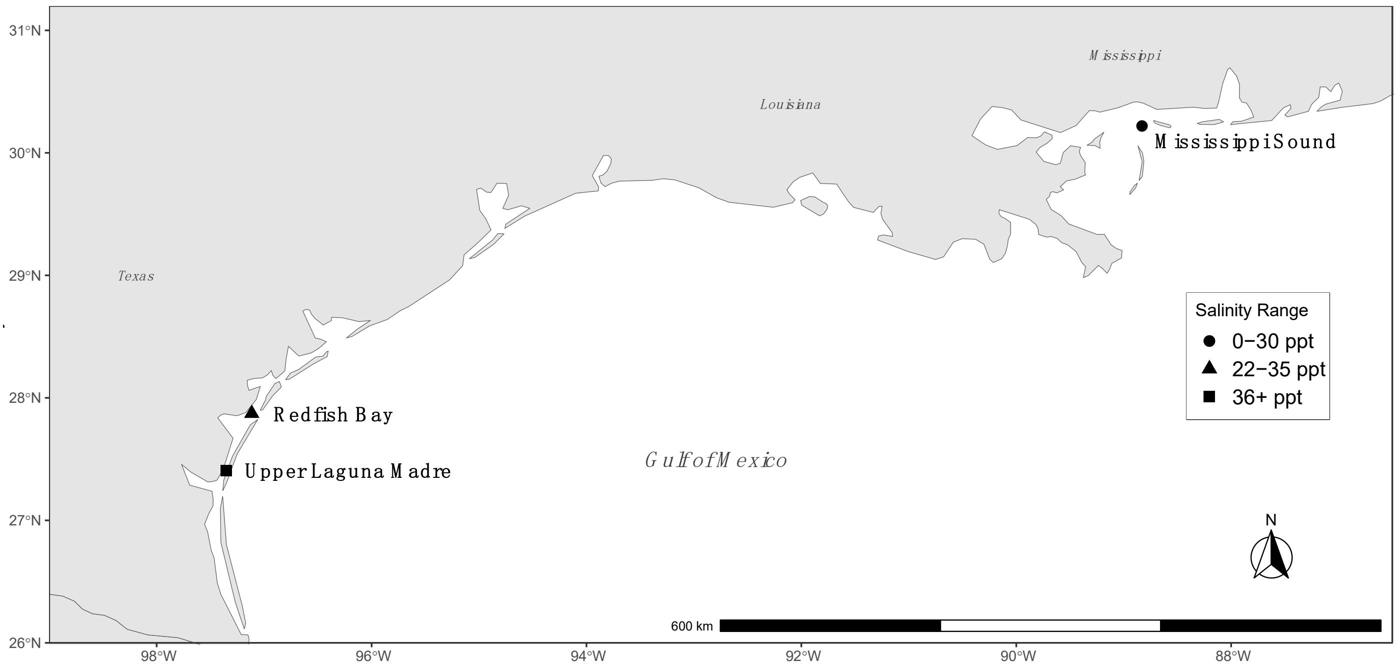


Figure 1. Map indicating where dolphins were photographed in Gulf of Mexico waters during surveys. Sampling locations included Redfish Bay, TX (2012–2014, 2022), Upper Laguna Madre, TX (2022), and Western Mississippi Sound, MS (2013). The symbols denote average salinity ranges.

Dolphin groups (individuals within 10 m of one another engaged in the same predominant behavioral state [40]) were photographed from a research vessel across all seasons (Table 1). Photographs of the dorsal fin (for subsequent identification) and the visible body of all dolphins in each group were collected using a Sony Cyber-Shot RX10 IV (2022) or Canon EOS 60D (2012–2014) camera. The photographer was positioned perpendicular and approximately 3–7 m from the dolphins in optimal lighting when possible. Once all dolphins in the group had been photographed, data on water parameters (temperature and salinity measured using a YSI pro-solo), environmental conditions (wind speed, air temperature, water depth, Beaufort Sea State), and group composition (number of dolphins, age classes, predominant behavioral states) were recorded. Rainfall during the sampling period was not recorded or assessed relative to salinity or water temperature.

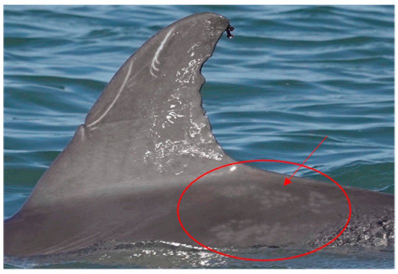
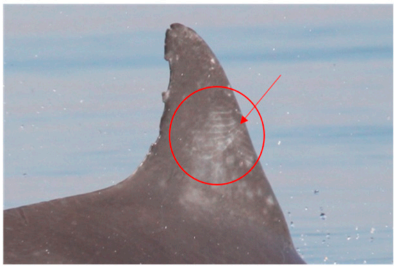
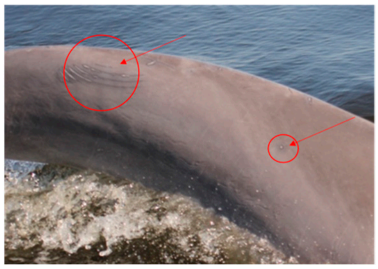
Table 1. Survey efforts for Redfish Bay (TX), Upper Laguna Madre (TX), and Mississippi Sound (MS). For each site, the corresponding season (month), year, number of days surveyed, and size of area surveyed are listed. The geographical area surveyed was approximately the same for all efforts at each site.

Site	Season (Month)	Year(s)	Days Surveyed	Survey Area (km^2)
Redfish Bay	Summer (June)	2012	11	56
	Summer (June)	2013	1	56
	Summer (June)	2014	2	56
	Spring (May)	2022	7	56
	Fall (November)	2022	4	56
Upper Laguna Madre	Spring (May)	2022	3	46
	Fall (November)	2022	2	46
Mississippi Sound	Winter (January)	2013	6	643
	Summer (August)	2013	6	643

All photographs of dolphins were carefully analyzed for the presence of lesions. Photographs were matched across seasons and years using finFindR [41] to identify individual dolphins. All photographs captured of a unique dolphin during the same season and year were used to determine whether lesions were present. Photographs were preliminarily filtered based on the amount of visible body (head, abdomen, and peduncle), image angle (ideally perpendicular to the dorsal fin), clarity (not blurry nor pixelated), and exposure (not backlit). Photographs with <10% of the body visible or that were approximately >20° offset from perpendicular, blurry, pixilated, or backlit were not analyzed further. A visual reference catalog [28] was used to aid in scoring images on the presence of lesions (0 = no lesion detected, 1 = lesion(s) detected). Two of the coauthors (MAG and CNT) independently evaluated 20% of the retained photographs to ensure reliability in lesion identification. Once an acceptable level of reliability was established (i.e., the level of agreement (K) was significantly $\geq$ 0.50), one coauthor (MAG) scored the remaining 80% of the photographs and consulted with the other when uncertain.

Positive lesion cases were identified when dolphins had a lesion(s) on either the left or right side of their body in any photograph. Negative cases (no lesion present) required images of both sides of a dolphin's body for confirmation; if both sides were not captured, the case was not included in analyses. Retained photographs of both positive and negative cases were evaluated based on image quality (Table 2), lesion characteristics, and reviewer confidence (scored as poor, intermediate, or high). High-quality images were required for further consideration unless reviewer confidence in the presence or absence of lesions was high. A minimum of five lesions approximately $\geq$20 mm in size (estimated) were needed to designate a positive case, including lesions near tooth rake marks, shark bites, and propeller/entanglement wounds (Table 2). Orange hue was excluded as a lesion type unless the dolphin had overlying lesions or previous documentation of lesions underneath the orange hue. If all image and lesion criteria were met and reviewer confidence was intermediate or high, the case was included in statistical analyses. Images that met photo quality and lesion criteria but had poor reviewer confidence were retained in analyses but scored as negative cases to avoid artificially inflating prevalence estimates. The prevalence of lesions (total number of dolphins with lesions/total number of dolphins with left and right images $\times$ 100%) was calculated per year for each stock and reported as a percentage of the total stock that was photographed.

Table 2. Criteria used to evaluate photographs of dolphin bodies for the presence of skin lesions following the methods outlined in [28]. Useable images include examples of those that met the criteria and could be included in statistical analyses, whereas non-useable images did not meet all criteria and were excluded. Red circles and arrows depict lesioned and/or wounded areas of skin.

Criteria	Description	Useable Image	Non-Useable Image
Image quality	In focus; <20° offset from perpendicular; not backlit, pixelated, nor blurry.		
Size and number of spots	>5 clustered lesion spots; approximately >20 mm in size		
Wound-related spots	On rake marks, shark bites, and/or propeller/entanglement wounds		

Additional demographic data (i.e., sex) were available when dolphin photography was paired with remote biopsy sampling, a method to collect biological tissue that does not require direct handling. Sex demographics on dolphins sampled from 2012 to 2014 were provided by the NOAA Southeast Fisheries Science Center's Marine Mammal Molecular Genetics lab. The sex demographics of dolphins sampled in 2022 were determined following the protocol outlined in [42] (Table S1).

Statistical analyses were conducted in R software (v.4.1.2). All data were tested for assumptions of normality and homogeneity of variance. Reviewer reliability in lesion identification was estimated by calculating Cohen's Kappa (K), a measure of agreement, and tested for significance using a z-test (Ho: $K \geq 0.50$), where $K = 0$ indicates a level of agreement due to chance alone, and $K = 1$ or -1 indicates complete agreement or disagreement, respectively. Additional metrics were calculated to account for prevalence and bias effects, which can easily impact the kappa test and reduce its interpretive power [28,43]. Additional metrics included the prevalence index (PI; the difference in the proportion of positive and negative cases, range 0–1; 0 = equivalent number of positive and negative cases) [43,44], the bias index (BI; extent of disagreement between positive and negative cases, range 0–1; 0 = absolute symmetrical agreement) [43,44], prevalence-adjusted bias-adjusted kappa (PABAK), and K_{max}. Reviewer bias effects were tested for significance ($\alpha = 0.05$) using a McNemar test, which evaluates differences in a dichotomous variable (i.e., lesion presence) between paired subjects (i.e., reviewers). Scoring of 20% of the data by two independent coauthor reviewers revealed high reviewer reliability (91% agreement;

$K = 0.82$; $z = 12.74$; SE = 0.06; CI: 0.69–0.95) with no evidence of bias effects (McNemar test; $n = 80$, $p = 0.06$; Table 3).

Table 3. Reviewer reliability test of the level of agreement in skin lesion identification. Frequency denotes the number of positive cases (lesion present) identified by each reviewer in the preliminary scoring of 20% of the dataset. Cohen's Kappa (K) indicates the level of agreement between reviewers, accounting for chance. The Prevalence Index (PI) indicates the difference between the probability of positive and negative cases. The Bias Index (BI) indicates the difference in the proportion of positive cases. PABAK reflects the corrected K accounting for PI and BI. Kmax is the maximum attainable K given the difference in the proportions of positive classifications between raters.

Frequency Reviewer #1	Frequency Reviewer #2	K	Agreement (%)	Chance Agreement (%)	PI	BI	PABAK	Kmax
37	42	0.82	91	50	0.01	−0.06 [ns]	0.82	0.95

[ns] The McNemar test on the bias effects was not significant.

Once reviewer reliability was established, differences in the prevalence of skin lesions were assessed spatially (across sites) and temporally (across seasons). The overall prevalence of skin lesions was compared between sites using a Chi-square test. Logistic regression analyses were used to assess relationships between lesion prevalence and salinity (continuous nominal measurements), water temperature (continuous nominal measurements), season (Spring: March–May; Summer: June–August; Fall: September–November; Winter: December–February), and sex (male, female, undetermined), when available, across all sites. The variance inflation factor (VIF) was measured to determine multicollinearity between variables, where VIF ≤ 1 indicates no correlation, 1–5 indicates a moderate correlation, and >5 indicates a strong correlation for which variables should be removed [45].

3. Results

A total of 867 unique dolphins were photographed (Table 4); after photographs were screened for photo quality, 432 dolphins were subsequently assessed for lesions. Across all sites, 191 dolphins were scored as positive cases, and 241 were scored as negative cases (Table 4). Lesion prevalence was generally highest in Upper Laguna Madre, followed by Mississippi Sound, then Redfish Bay. Seasonal variations in salinity and water temperature are described in Figure S1. Since surveys were conducted without physically handling dolphins, the sex of individuals is unknown except for the animals also sampled by remote biopsy (Table S2, $n = 44$ dolphins).

Table 4. Number (#) of unique dolphins photographed and assessed for skin lesions. Screening criteria were applied to generate the number (#) of unique dolphins assessed.

Site	Season (Month)	Year(s)	# Unique Dolphins Sighted	# Unique Dolphins Assessed	# Positive Lesion Cases (Prevalence %)
Redfish Bay	Summer (June)	2012	198	99	39 (39)
	Summer (June)	2013	51	26	8 (31)
	Summer (June)	2014	36	21	3 (14)
	Spring (May)	2022	144	50	12 (24)
	Fall (November)	2022	85	41	25 (61)
Upper Laguna Madre	Spring (May)	2022	74	34	18 (53)
	Fall (November)	2022	29	20	14 (70)
Mississippi Sound	Winter (January)	2013	95	56	30 (54)
	Summer (August)	2013	200	85	42 (49)

Regression models indicated no collinearity concerns (all VIF values $\leq$ 1.5). The prevalence of lesions was not significantly related to salinity level (z_{431} = −1.3, p = 0.2); however, cumulative lesion prevalence across all seasons in high saline waters (ULM) and low saline waters (MS) was greater than that in approximately average saline conditions (RB) (Table 4). Lesions were observed on dolphins in all three sites and were significantly related to season ($R^2{}_3$ = 20.4, p = 0.001). In RB, lesions were significantly more prevalent in the fall than in the spring or summer ($X^2{}_2$ = 41.4, p < 0.001; Table 4). The highest prevalence of lesions during the spring and summer months occurred in the summer of 2012 (Table 4). A total of 36 dolphins were resighted between the 2012–2014 and 2022 survey periods in RB, of which 7 dolphins (n_{2012} = 5, n_{2022} = 2) exhibited lesions that were only documented in the summer of 2012 and fall of 2022. In ULM, the prevalence of lesions was higher in the fall than in the spring, although not statistically significant ($X^2{}_1$ = 1.518, p = 0.2; Table 4). Two of the four dolphins resighted in ULM between spring and fall had lesions, and lesions on these dolphins were only documented in the fall. In MS, more dolphins had lesions in the winter than in the summer, although not statistically significant ($X^2{}_1$ = 1.043, p = 0.3; Table 4). Two of the five dolphins resighted in MS between winter and summer had lesions, and lesions on these dolphins were present during both seasons. A strong negative correlation was found between lesion prevalence and water temperature (r_{430} = −0.14, p = 0.003); lesions were most prevalent on dolphins in all stocks when ambient water temperature was the lowest (i.e., fall and winter; Table 4). No relationship was identified between lesion prevalence and dolphin sex (z_{43} = 0.03, p = 0.9).

4. Discussion

Environmental conditions are becoming increasingly variable along the coastal GoM as climate change intensifies extreme weather events. Pulses of severe weather can impose physiological stress on apex marine organisms like dolphins, and altered conditions may persist for long periods of time [46,47]. This study is the first to assess the epidermal condition of dolphins across a salinity gradient that includes hypersaline levels. We demonstrate that lesion prevalence in dolphins varies with season, seemingly more as a factor of water temperature than salinity, although other variables may be important predictors. Understanding the impacts of environmental variability on habitat structure, ecosystem dynamics, and species adaptability is crucial for sustainable management and consideration of potential human health concerns.

Skin lesions on dolphins are widespread and affect large proportions of populations around the world [21]. Dolphin skin is the first protective barrier against ambient stressors and is sensitive to fluctuations in salinity. Hydropic degeneration (i.e., fluid accumulation and epithelial cell swelling) resulting from prolonged exposure to salinities < 10 ppt typically precedes epidermal lesions that may lead to secondary infection and mortality [10,11,14,48]. In natural high-saline waters, however, epidermal wounds on dolphins appear to heal faster than in average saline conditions [39], likely due to the anti-inflammatory and anti-bacterial properties of sodium. In this study, salinity did not exhibit a significant effect on lesion prevalence; however, a high prevalence of lesions was observed in ULM dolphins in high-saline waters, similar to the prevalence of lesions seen in the MS stock in low-saline waters. Additionally, the prevalence of lesions in RB during the summer of 2012, when ambient salinity levels were nearly 38 ppt, was significantly higher than in 2022, when salinities were 32–33 ppt. Unusually high salinities in 2012 were linked to a La Niña event and the most severe 1-year drought in Texas' history, which began in 2011 [49]. The high prevalence of lesions on dolphins despite high ambient salinity may indicate that lesion development is linked to additional factors that may be exacerbated by hypersaline conditions.

Multiple stressors acting on and within the water column may be amplified by high salinity. For instance, the skin microbiome of dolphins is sensitive to changes in water chemistry, and high salinities may support a unique microbial community that is conducive to lesion proliferation. High salinity generally decreases the solubility of organic pollutants, which may enhance their bioavailability and affinity for lipophilic tissues (i.e., blubber) where lesion development ensues [24,50]. With previous reports of contamination in RB and ULM by metals, pesticides, and other organic compounds [31], it is important to understand the potential for high salinity to amplify the toxicity of organic pollutants and inflate lesion prevalence. Increased salinities may also intensify changes in the pH of dolphin skin and, like human skin, contribute to the pathogenesis of skin disease [51]. With increasing environmental perturbations resulting from climate change, alterations in water chemistry are especially important to consider. In the southwestern United States, major weather events like La Niña are leading to increasingly hot and dry climates, which raise salinity levels, reduce precipitation and streamflow, and increase evaporation rates [52,53]. Estuary dewatering, upstream diversions, and industrial brine discharge from oil, gas, and desalination plants also reduce freshwater inflow into bays, sounds, and estuarine systems [54,55]. Understanding how high salinity adversely affects the functional properties of dolphin skin and alters their adaptability in complex environments is crucial for interpreting how dolphin tissue can be utilized for biomonitoring. For instance, a better understanding of the predominant route of marine toxin accumulation in dolphin tissue (i.e., ingestion or skin absorption) would be important for establishing the relationship between salinity, toxin bioavailability, and subsequent trophic cascades. In regions where marine ecotourism and fishing are important economic contributors, studies of dolphin skin as a biomarker of environmental contaminant loads could benefit human communities by informing policymakers on ecosystem health to promote more sustainable development.

Like salinity, rapid changes in water temperature can also have negative effects on dolphin skin. A negative relationship between lesion occurrence and water temperature has been found in other studies, demonstrating that lesions may be most prevalent when ambient waters are cool [10,11]. Dolphin susceptibility to viable pathogens and disease may be heightened in cold waters; cold-water exposure may limit blood flow to the skin and impede immune protection, reducing epidermal cell regeneration [56]. Shifts in the microbial community inhabiting dolphin skin during cold water exposure may also render dolphins more susceptible to lesions and secondary diseases [57]. The decrease in water temperature between seasons was most pronounced during the winter in MS. Five months prior to the winter survey in MS, Hurricane Isaac inundated southern Mississippi with >10 inches of rain [58] and drastically reduced ambient salinity levels. Cold waters compounded by low salinity may have resulted in the patterns of observed lesions. For example, generalized or diffuse epidermal pallor is often the first progressive stage of freshwater exposure [1,28,48] and was most prevalent in the MS stock. The rapid input of terrestrial contaminants into MS from storm surge may also have contributed to lesion development. The connection between a major weather event and changes in epidermal condition suggests the capacity of dolphin skin to reflect environmental disturbance.

Integrating archived and newly collected images of dolphins from RB provided a holistic overview of how changes over time may influence dolphin health and reflect ecosystem quality. In 2015, following the 2012–2014 survey period, a global oil exportation ban was lifted, and the shipping channel adjacent to RB experienced a major influx in vessel activity [32,33]. Progress on a multi-million dollar dredging project has since ensued to broaden and deepen the channel to accommodate larger vessels and trade operations [33]. Large-scale channel dredging may increase the abundance of contaminants in the water column, which can bioaccumulate in dolphin skin tissue and precede or heighten lesion development. However, our data do not support this hypothesis. While the 2011 drought spiked lesion prevalence in 2012, overall lesion prevalence was approximately consistent between 2012–2014 and 2022 in RB, indicating that dolphins may have adapted to the increasing development and port activity in the area or that the impacts of dredging were not fully captured in the short window of survey effort conducted in 2022. Nonetheless, it remains crucial to understand how large-scale climate changes that influence marine water chemistry may compound the effects of dredging activities and other channel modifications in coastal areas. The historical presence of pesticides and heavy metals like zinc and mercury in RB from industrial operations and superfund sites raises concerns about their continued persistence and bioavailability in the ecosystem as a result of commercial dredging [31].

The addition of skin lesion data to fill temporal gaps in our study may add new insights and help elucidate the connection between industrial activity and marine ecosystem health. Incorporating regional precipitation data could strengthen our interpretation of the observed shifts in salinity and water temperature that directly influence seasonal lesion prevalence. Although images are useful tools for assessing disease in dolphin populations, it is difficult to generalize physiological change without biological tissue. However, we acknowledge the opportunistic nature of the study and the caveats that limit our ability to generalize retrospective conclusions. Despite varied efforts across space and time, a conservative approach was taken to mitigate biases; comparable numbers of positive and negative cases were reported for each site cumulatively, suggesting conservative estimates of lesion prevalence and important biological relationships relative to environmental conditions. Future work to determine the biologically useful information that can be derived from images and applied to free-ranging dolphin research can help identify at-risk populations during rapid environmental change.

5. Conclusions

This study supports growing evidence that variable conditions, including salinity, water temperature, and the compounded effects of severe weather, render dolphins susceptible to epidermal lesions. Additional variables that may influence lesion development include organic pollutants and pH level, although the variability of these factors across sites and their overall influence on epidermal disease in dolphins remains poorly understood. We demonstrate the drawbacks of visual-only assessments and the challenges of elucidating biologically important information when tissue samples are unavailable. Bottlenose dolphins are valuable study organisms often characterized as bioindicator species, implying the potential for dolphin skin to be a meaningful tool in assessments of environmental quality and dolphin physiology. Future studies of free-ranging dolphin populations are needed to explore the complex role of multiple stressors on skin lesion development and elucidate the potential link to human health.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16104260/s1. Table S1: Primer sequences for bottlenose dolphin sex determination; Table S2: Demographic data for photographed dolphins with paired biopsy samples; Figure S1: Box plots of the range of seasonal variation in (a) salinity (ppt) and (b) water temperature (°C) in Redfish Bay, TX (2012–2014, 2022), Upper Laguna Madre, TX (2022), and Western Mississippi Sound, MS (2013).

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request from the corresponding authors.

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References

1. Ewing, R.Y.; Mase-Guthrie, B.; McFee, W.; Townsend, F.; Manire, C.A.; Walsh, M.; Borkowski, R.; Bossart, G.D.; Schaefer, A.M. Evaluation of serum for pathophysiological effects of prolonged low salinity water exposure in displaced bottlenose dolphins (*Tursiops truncatus*). *Front. Vet. Sci.* **2017**, *4*, 80. [CrossRef]
2. Hornsby, F.; McDonald, T.; Balmer, B.; Speakman, T.; Mullin, K.; Rosel, P.; Wells, R.; Telander, A.; Marcy, P.; Schwacke, L. Using salinity to identify common bottlenose dolphin habitat in Barataria Bay, Louisiana, USA. *Endanger. Species Res.* **2017**, *33*, 181–192. [CrossRef]
3. McClain, A.M.; Daniels, R.; Gomez, F.M.; Ridgway, S.H.; Takeshita, R.; Jensen, E.D.; Smith, C.R. Physiological effects of low salinity exposure on bottlenose dolphins (*Tursiops truncatus*). *J. Zool. Bot. Gard.* **2020**, *1*, 61–75. [CrossRef]
4. Trenberth, K. Changes in precipitation with climate change. *Clim. Res.* **2011**, *47*, 123–138. [CrossRef]
5. Olson, J.R. Predicting combined effects of land use and climate change on river and stream salinity. *Philos. Trans. R. Soc. B Biol. Sci.* **2018**, *374*, 20180005. [CrossRef] [PubMed]
6. Takeshita, R.; Balmer, B.C.; Messina, F.; Zolman, E.S.; Thomas, L.; Wells, R.S.; Smith, C.R.; Rowles, T.K.; Schwacke, L.H. High site-fidelity in common bottlenose dolphins despite low salinity exposure and associated indicators of compromised health. *PLoS ONE* **2021**, *16*, e0258031. [CrossRef] [PubMed]
7. Toms, C.N.; Stone, T.; Och, T. Skin lesion and mortality rate estimates for common bottlenose dolphin (*Tursiops truncatus*) in the Florida Panhandle following a historic flood. *PLoS ONE* **2021**, *16*, e0257526. [CrossRef]
8. Tunnell, J.W.; Judd F., W. *The Laguna Madre of Texas and Tamaulipas, Revised ed.*; Texas A&M University Press, U.S.: College Station, TX, USA, 2002; 346p.
9. Mullin, K.; Barry, K.; Sinclair, C.; Litz, J.; Maze-Foley, K.; Fougeres, E.; Mase, B.; Ewing, R.; Gorgone, A.; Adams, J.; et al. *Common Bottlenose Dolphins (Tursiops truncatus) in Lake Pontchartrain, Louisiana: 2007 to Mid-2014*; NOAA Technical Memorandum NMFS-SEFSC-673; National Oceanic and Atmospheric Administration: Pascagoula, MS, USA, 2015. [CrossRef]
10. Duignan, P.J.; Stephens, N.S.; Robb, K. Fresh water skin disease in dolphins: A case definition based on pathology and environmental factors in Australia. *Sci. Rep.* **2020**, *10*, 1–17. [CrossRef] [PubMed]
11. Hart, L.B.; Rotstein, D.S.; Wells, R.S.; Allen, J.; Barleycorn, A.; Balmer, B.C.; Lane, S.M.; Speakman, T.; Zolman, E.S.; Stolen, M.; et al. Skin lesions on common bottlenose dolphins (*Tursiops truncatus*) from three sites in the Northwest Atlantic, USA. *PLoS ONE* **2012**, *7*, e33081. [CrossRef]
12. Van Bressem, M.-F.; Raga, J.A.; Di Guardo, G.; Jepson, P.D.; Duignan, P.J.; Siebert, U.; Barrett, T.; Santos, M.C.d.O.; Moreno, I.B.; Siciliano, S.; et al. Emerging infectious diseases in cetaceans worldwide and the possible role of environmental stressors. *Dis. Aquat. Org.* **2009**, *86*, 143–157. [CrossRef]
13. Wilson, B.; Arnold, H.; Bearzi, G.; Fortuna, C.M.; Gaspar, R.; Ingram, S.; Liret, C.; Pribanic, S.; Read, A.J.; Ridoux, V.; et al. Epidermal diseases in bottlenose dolphins: Impacts of natural and anthropogenic factors. *Proc. R. Soc. B Biol. Sci.* **1999**, *266*, 1077–1083. [CrossRef] [PubMed]
14. Croft, L.A.; Laughlin, R.; Manley, M.; Nollens, H.H. Water temperature fluctuations as a key driver of cetacean pox (tattoo) lesions in bottlenose dolphins *Tursiops truncatus*. *Dis. Aquat. Org.* **2020**, *139*, 69–79. [CrossRef] [PubMed]
15. Maldini, D.; Riggin, J.; Cecchetti, A.; Cotter, M.P. Prevalence of epidermal conditions in California coastal bottlenose dolphins (*Tursiops truncatus*) in Monterey Bay. *AMBIO* **2010**, *39*, 455–462. [CrossRef] [PubMed]
16. Geraci, J.R. Clinical investigation of the 1987–1988 mass mortality of bottlenose dolphins along the US central and south Atlantic coast. In *National Marine Fisheries Service and US Navy Office of Naval Research and Marine Mammal Commission Report 1078*; Ontario Veterinary College: Guelph, ON, Canada, 1989; p. 63.
17. Kuehl, D.W.; Haebler, R. Organochlorine, organobromine, metal, and selenium residues in bottlenose dolphins (*Tursiops truncatus*) collected during an unusual mortality event in the Gulf of Mexico, 1990. *Arch. Environ. Contam. Toxicol.* **1995**, *28*, 494–499. [CrossRef]
18. Miller, A.H.; Maletic, V.; Raison, C.L. Inflammation and its discontents: The role of cytokines in the pathophysiology of major depression. *Biol. Psychiatry* **2009**, *65*, 732–741. [CrossRef] [PubMed]
19. Morey, J.N.; Boggero, I.A.; Scott, A.B.; Segerstrom, S.C. Current directions in stress and human immune function. *Curr. Opin. Psychol.* **2015**, *5*, 13–17. [CrossRef]
20. Irwin, L.-J. Marine toxins: Adverse health effects and biomonitoring with resident coastal dolphins. *Aquat. Mamm.* **2005**, *31*, 195. [CrossRef]

21. Mouton, M.; Both, A. Cutaneous lesions in cetaceans: An indicator of ecosystem status? In *New Approaches to the Study of Marine Mammals*; Romero, A., Ed.; InTechOpen: Rijeka, Croatia, 2012. [CrossRef]
22. Yordy, J.E.; Wells, R.S.; Balmer, B.C.; Schwacke, L.H.; Rowles, T.K.; Kucklick, J.R. Partitioning of persistent organic pollutants between blubber and blood of wild bottlenose dolphins: Implications for biomonitoring and health. *Environ. Sci. Technol.* **2010**, *44*, 4789–4795. [CrossRef] [PubMed]
23. Cáceres-Saez, I.; Goodall, R.N.P.; Dellabianca, N.A.; Cáceres-Saez, I.; Goodall, R.N.P.; Dellabianca, N.A.; Cappozzo, H.L.; Guevara, S.R. The skin of Commerson's dolphins (*Cephalorhynchus commersonii*) as a biomonitor of mercury and selenium in Subantarctic waters. *Chemosphere* **2015**, *138*, 735–743. [CrossRef]
24. Todd, V.L.G.; Todd, I.B.; Gardiner, J.C.; Morrin, E.C.N.; MacPherson, N.A.; DiMarzio, N.A.; Thomsen, F. A review of impacts of marine dredging activities on marine mammals. *ICES J. Mar. Sci.* **2015**, *72*, 328–340. [CrossRef]
25. Soares, E.D.; Cantor, M.; Bracarense, A.P.F.R.L.; Groch, K.R.; Domit, C. Health conditions of Guiana dolphins facing cumulative anthropogenic impacts. *Mamm. Biol.* **2022**, *102*, 1589–1604. [CrossRef]
26. Mora, C.; McKenzie, T.; Gaw, I.M.; Dean, J.M.; von Hammerstein, H.; Knudson, T.A.; Setter, R.O.; Smith, C.Z.; Webster, K.M.; Patz, J.A.; et al. Over half of known human pathogenic diseases can be aggravated by climate change. *Nat. Clim. Chang.* **2022**, *12*, 869–875. [CrossRef] [PubMed]
27. Bearzi, M.; Rapoport, S.; Chau, J.; Saylan, C. Skin lesions and physical deformities of coastal and offshore common bottlenose dolphins (*Tursiops truncatus*) in Santa Monica Bay and adjacent areas, California. *AMBIO* **2009**, *38*, 66–71. [CrossRef] [PubMed]
28. Toms, C.N.; Stone, T.; Och-Adams, T. Visual-only assessments of skin lesions on free-ranging common bottlenose dolphins (*Tursiops truncatus*): Reliability and utility of quantitative tools. *Mar. Mammal Sci.* **2020**, *36*, 744–773. [CrossRef]
29. Wursig, B.; Jefferson, T.A. Methods of photo identification for small cetaceans. In *Report of the International Whaling Commission*; Special Issue 12; International Whaling Commission: Cambridge, UK, 1990; pp. 43–52.
30. Ewing, R.Y.; Sutton, M.N.; Herring, H.M.; Schubert, M.R.; Boyd, D.M.; Richardson, J.L.; Rotstein, D.S. Standardizing gross descriptions of skin lesions in common bottlenose dolphins (*Tursiops truncatus*) stranded in Southwest Florida, 2015–2019. *Front. Mar. Sci.* **2023**, *10*, 1269075. [CrossRef]
31. Phillips, N.M.; Rosel, P.E. A method for prioritizing research on common bottlenose dolphin stocks through evaluating threats and data availability: Development and application to bay, sound and estuary stocks in Texas. In *National Oceanic and Atmospheric Administration, Technical Memorandum NMFS-SEFSC-670*; National Marine Fisheries Service: Pascagoula, MS, USA, 2014; 154p. [CrossRef]
32. Port Corpus Christi. Available online: https://portofcc.com/about/port/about-us/ (accessed on 24 January 2024).
33. Mills, E.M.M.; Piwetz, S.; Orbach, D.N. Vessels disturb bottlenose dolphin behavior and movement in an active ship channel. *Animals* **2023**, *13*, 3441. [CrossRef] [PubMed]
34. Javor, B. *Hypersaline Environments: Microbiology and Biogeochemistry*; Springer: Berlin/Heidelberg, Germany, 1989; 328p.
35. Onuf, C.P. Laguna Madre. In *Seagrass Status and Trends in the Northern Gulf of Mexico: 1940–2002*; Handley, L., Altsman, D., DeMay, R., Eds.; U.S. Geological Survey: Reston, VA, USA, 2007; pp. 29–40.
36. Olsen, Z.T. Potential impacts of extreme salinity and surface temperature events on population dynamics of black drum, Pogonias cromis, in the Upper Laguna Madre, Texas. *Gulf Mex. Sci.* **2014**, *32*, 6. [CrossRef]
37. Vollmer, N.L.; Rosel, P.E.; Mullin, K.D.; Schwacke, L.H.; Garrison, L.P.; Balmer, B.C.; Barry, K.; Martinez, A.; Quigley, B.M.; Sinclair, C.; et al. Assessing common bottlenose dolphin (*Tursiops truncatus*) population structure in Mississippi Sound and coastal waters of the north central Gulf of Mexico. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2021**, *31*, 2951–2966. [CrossRef]
38. Lettrich, M.D.; Asaro, M.J.; Borggaard, D.L.; Dick, D.M.; Griffis, R.B.; Litz, J.A.; Orphanides, C.D.; Palka, D.L.; Soldevilla, M.S.; Balmer, B.; et al. Vulnerability to climate change of United States marine mammal stocks in the western North Atlantic, Gulf of Mexico, and Caribbean. *PLoS ONE* **2023**, *18*, e0290643. [CrossRef]
39. Hurst, B.; Orbach, D. Salinity affects wound healing in wild common bottlenose dolphins (*Tursiops truncatus*). *Am. J. Undergrad. Res.* **2022**, *19*, 23–29. [CrossRef]
40. Smolker, R.A.; Richards, A.F.; Connor, R.C.; Pepper, J.W. Sex differences in patterns of association among Indian Ocean bottlenose dolphins. *Behaviour* **1992**, *123*, 38–69. [CrossRef]
41. Thompson, J.W.; Zero, V.H.; Schwacke, L.H.; Speakman, T.R.; Quigley, B.M.; Morey, J.S.; McDonald, T.L. finFindR: Automated recognition and identification of marine mammal dorsal fins using residual convolutional neural networks. *Mar. Mammal Sci.* **2022**, *38*, 139–150. [CrossRef]
42. Rosel, P.E. PCR-based sex determination in Odontocete cetaceans. *Conserv. Genet.* **2003**, *4*, 647–649. [CrossRef]
43. Byrt, T.; Bishop, J.; Carlin, J. Bias, prevalence and kappa. *J. Clin. Epidemiol.* **1993**, *46*, 423–429. [CrossRef]
44. Sim, J.; Wright, C.C. The kappa statistic in reliability studies: Use, interpretation, and sample size requirements. *Phys. Ther.* **2005**, *85*, 257–268. [CrossRef] [PubMed]
45. Akinwande, M.O.; Dikko, H.G.; Samson, A. Variance inflation factor: As a condition for the inclusion of suppressor variable(s) in regression analysis. *Open J. Stat.* **2015**, *5*, 754–767. [CrossRef]
46. Greening, H.; Doering, P.; Corbett, C. Hurricane impacts on coastal ecosystems. *Estuaries Coasts* **2006**, *29*, 877–879. [CrossRef]
47. Fazioli, K.; Mintzer, V. Short-term effects of hurricane Harvey on bottlenose dolphins (*Tursiops truncatus*) in upper Galveston Bay, TX. *Estuaries Coasts* **2020**, *43*, 1013–1031. [CrossRef]

48. Deming, A.C.; Wingers, N.L.; Moore, D.P.; Rotstein, D.; Wells, R.S.; Ewing, R.; Hodanbosi, M.R.; Carmichael, R.H. Health impacts and recovery from prolonged freshwater exposure in a common bottlenose dolphin (*Tursiops truncatus*). *Front. Vet. Sci.* **2020**, *7*, 235. [CrossRef]
49. Fernando, D.N.; Mo, K.C.; Fu, R.; Pu, B.; Bowerman, A.; Scanlon, B.R.; Solis, R.S.; Yin, L.; Mace, R.E.; Mioduszewski, J.R.; et al. What caused the spring intensification and winter demise of the 2011 drought over Texas? *Clim. Dyn.* **2016**, *47*, 3077–3090. [CrossRef]
50. Hutton, S.J.; Romain, S.J.S.; Pedersen, E.I.; Siddiqui, S.; Chappell, P.E.; White, J.W.; Armbrust, K.L.; Brander, S.M. Salinity alters toxicity of commonly used pesticides in a model euryhaline fish species (*Menidia beryllina*). *Toxics* **2021**, *9*, 114. [CrossRef] [PubMed]
51. Schmid-Wendtner, M.-H.; Korting, H. The pH of the skin surface and its impact on the barrier function. *Ski. Pharmacol. Physiol.* **2006**, *19*, 296–302. [CrossRef] [PubMed]
52. Seager, R.; Ting, M.; Held, I.; Kushnir, Y.; Lu, J.; Vecchi, G.; Huang, H.-P.; Harnik, N.; Leetmaa, A.; Lau, N.-C.; et al. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **2007**, *316*, 1181–1184. [CrossRef] [PubMed]
53. Miller, O.L.; Putman, A.L.; Alder, J.; Miller, M.; Jones, D.K.; Wise, D.R. Changing climate drives future streamflow declines and challenges in meeting water demand across the southwestern United States. *J. Hydrol.* **2021**, *11*, 100074. [CrossRef]
54. Asquith, W.H.; Mosier, J.G.; Bush, P.W. *Status, Trends, and Changes in Freshwater Inflows to Bay Systems in the Corpus Christi Bay National Estuary Program Study Area*; United States Geological Survey: Austin, TX, USA, 1997.
55. Montagna, P.A.; Coffey, D.M.; Jose, R.H.; Stunz, G.W. *Vulnerability Assessment of Coastal Bend Bays*; Report CBBEP—152; Texas A&M University: Corpus Christi, TX, USA, 2021.
56. Feltz, E.T.; Fay, F.H. Thermal requirements in vitro of epidermal cells from seals. *Cryobiology* **1966**, *3*, 261–264. [CrossRef]
57. Carmichael, R.H.; Graham, W.M.; Aven, A.; Worthy, G.; Howden, S. Were multiple stressors a 'perfect storm' for northern Gulf of Mexico bottlenose dolphins (*Tursiops truncatus*) in 2011? *PLoS ONE* **2012**, *7*, e41155. [CrossRef]
58. Berg, R. Tropical cyclone report hurricane Isaac 21 August–1 September 2012. In *National Hurricane Center Report AL092012*; National Hurricane Center: Miami, FL, USA, 2013; p. 78.