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Weather patterns associated with green turtle (*Chelonia mydas*) hypothermic stunning in Corpus Christi Bay, Texas

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Abstract

Hypothermic stunning was the largest cause of green turtle (Chelonia mydas) stranding in Texas between 1998 and 2019; of the 9,256 individuals stranded, 7,956 (85.96%) were due to cold stunning. In cold conditions, Chelonia mydas migrate from shallow feeding areas to warmer waters. Unexpected drops in temperature, however, can cause a hypothermic reaction (cold stunning) immobilising large populations and becoming fatal if individuals are not rescued and rehabilitated quickly. This study aims to evaluate the influence of changes in environmental parameters to the magnitude of hypothermic stunning events within Corpus Christi Bay, Texas, U.S.

Measurements of sea surface temperature, air temperature, wind speed and wind direction from Bob Hall Pier were compared to pressure records from Corpus Christi Central City Station and Sea Turtle Stranding and Salvage Network (STSSN) cold stun reports for the duration of hypothermic seasons with varying degrees of severity: low (2012-2013), moderate (2009-2010), high (2014-2015), severe (2017-2018). Changes to atmospheric variables during the formation/progression of cold fronts over Corpus Christi Bay were observed to drive decreases in sea surface temperature, subsequently causing hypothermia in juvenile Chelonia mydas. Event severity was attributed to frequency and duration of frigid sea surface temperature exposure rather than water temperature cooling rate.

While previous studies attribute cold stun events to water temperatures below 10°C, this is an ineffective predictor of cold stunning as using a 10°C threshold predicted days of cold stun reports and not events in advance. Alternatively, this study suggests using a 10°C maximum air temperature combined with a 1020mb minimum surface air pressure threshold as an in advance prediction method. This approach successfully predicted the cold stunning of 86.49% of individuals when highlighting distinct cold stun days, or 97.72% of individuals when the day marked the start of a hypothermic stunning event. These results suggest using the development and passage of cold fronts as an in advance prediction of cold stun events to improve response times and minimise the impact on green turtle populations.

Keywords: green turtle (Chelonia mydas), hypothermic season, cold stun, Corpus Christi Bay, sea surface temperature, air temperature, wind speed, wind direction, pressure, cold front.

Introduction
Marine reptiles experience a hypothermic reaction referred to as cold stunning when exposed to frigid temperatures for long periods. Turtles, including the green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), Kemp's ridley (*Lepidochelys kempii*) and loggerhead (*Caretta caretta*) species are particularly impacted, with green turtles, especially juveniles, being affected most frequently (Shaver *et al*., 2017; Witherington and Ehrhart, 1989). Usually when water temperatures become too cold, turtles migrate from shallow feeding areas to warmer waters (Lutz and Musick, 1997; Roberts *et al*., 2013). However, unexpected drops in temperature can cause hypothermic stunning events immobilising large populations of sea turtles (Shaver *et al.*, 2017; Witherington and Ehrhart, 1989). Prolonged exposure to frigid temperatures can disrupt turtles' metabolic pathways and blood chemistry (Foley *et al*., 2007) causing individuals to become disorientated and lethargic (Witherington and Ehrhart, 1989), float at the surface, or be washed ashore (in extreme cases) (Roberts *et al*., 2013).

Controlled experiments by Schwartz (1978) indicated green turtles become cold stunned at 10°C, with temperatures becoming lethal between 5-6°C. However, if individuals can be rescued and rehabilitated quickly, hypothermic stunning events usually have low mortality rates (Roberts *et al*., 2013). A cold stun event can be categorised as either acute or chronic (Foley *et al*., 2007): acute events are short-lived occurring during uncharacteristically cold winters, whereas chronic events occur annually and are longer lasting (Foley *et al*., 2007; Roberts *et al*., 2013). Results from previous studies found no noticeable difference in mortality between acute or chronic events (Schwartz, 1978), suggesting cold stun event severity to be less reliant on the duration of cold exposure and determined instead by environmental parameter threshold values. Acute hypothermic stunning events have been reported along the U.S. Atlantic Ocean and Gulf of Mexico coast (Foley *et al*., 2007; Mendonca, 1981; Schwartz, 1978; Williams *et al*., 2013), Hawaii (Brill *et al.*, 1995) and Western Europe (Brongersma, 1982; Davenport, 1997).

Texas coastal waters provide essential foraging and developmental habitat for green turtles in the western Gulf of Mexico *(*Metz and Landry*, 2013;* Shaver *et al*., 2013, Shaver *et al*., 2017). The majority of green turtles in Texas waters are juveniles (Shaver, 2000) using passes and bays as developmental habitats between pelagic environments and lagoon feeding areas, or to manoeuvre between bays and the Gulf of Mexico (Coyne, 1994; Shaver, 2000). However, these waters cool more rapidly due to their shallow nature, causing turtles to become trapped in inlets or bays such as Corpus Christi Bay during cold stun periods of abnormally cold temperatures (Shaver *et al*., 2017).

Previous studies have indicated the need to quantify the magnitude of hypothermic stunning with changes to environmental variables that contribute to the event. Such studies have already been undertaken in Florida (Roberts *et al*., 2013), but more information is needed to quantify environmental parameters contributing to hypothermic stunning in other areas such as Texas (Shaver *et al*., 2017). This study aims to evaluate the influence of environmental parameters to the magnitude of hypothermic stunning events within Corpus Christi Bay, Texas, U.S.A. It is hoped that producing a quantitative analysis of environmental patterns associated with past events will allow for improved preparation and forecasting to better equip rehabilitation facilities and rescue organisations in the future.

The objectives of this study were to:

1) Describe the magnitude and temporal trends of green turtle hypothermic stunning events within Corpus Christi Bay between 1998-2019.
2) Graphically depict oceanic (water temperature) and atmospheric (air temperature, wind speed and direction, barometric pressure) parameters alongside the number of green turtles cold stunned for selected events to compare different levels of severity.
3) Determine the relationship between environmental parameters (water temperature, atmospheric variables and climate indexes) and the formation and severity of hypothermic stunning events within Corpus Christi Bay.

Methodology

Sea Turtle Documentation

The number of cold stunned turtles documented from 01/01/1998 to 01/01/2020 was established using the Sea Turtle Stranding and Salvage Network (STSSN) (Southeast Fisheries Science Center, 2022). The time period selected corresponds to when the STSSN first started to obtain online weekly reports of sea turtle strandings and when NOAA Galveston turned over the stranding network to the Houston Zoo and Texas A&M University at Galveston in September 2019 (personal communication, Benjamin Higgins (STSSN Data Steward), August 2021). Hence, data after 2020 is not currently directly available through the STSSN.

The selected area of study was the STSSN regional statistical zones 18, 19, 20 and 21 (predetermined by the network), corresponding to Texas state, U.S.A (Figure 2c). The STSSN documents stranded and incidentally captured (trapped in power plant intakes or as commercial/recreational fishing bycatch) turtles in response to reports or during systematic searches by the STSSN (Shaver *et al*., 2017). The type of stranding (i.e. cold stun, stranding, incidental capture), species, condition, zone and inshore/offshore location where the turtle was found were recorded on standardised forms and forwarded to national STSSN coordinators. Offshore entries are defined as beaches or waters of the Gulf of Mexico and inshore areas correspond to beaches or waters of passes and bays (Shaver *et al*., 2017). Hypothermic turtles found alive were taken for rehabilitation, applied with Inconel and Passive Integrated Transponder (PIT) tags (Balazs, 1999), and released where they had been found when waters warmed or in Gulf waters during large events where bay temperatures remained too low for longer which prolonged the rehabilitation timeframe (Shaver *et al*., 2017).

Turtle Data Analysis

Weekly stranding reports were compiled into a central Excel database and used to establish temporal and spatial distributions of hypothermic stunning events. For data analysis, only identifiable species which were either code 0 (alive) or code 1 (fresh dead) were included. Turtles reported in dried carcass, moderately decomposed, severely decomposed, skeleton and unknown conditions were excluded to examine near-real time impacts of the hypothermic stunning event in accordance with Shaver *et al.*, (2017).

Consistent with Shaver *et al.*, (2017) events were determined by the number of cold stunned turtles per hypothermic stunning season (November through March, designated by the year they began) and then categorised by severity. Events were classified according to the number of cold stunned turtles reported as either low (<30), moderate (30-200) or high (201-400) as specified by Roberts *et al.* (2013). An additional category severe (>400 cold stunned turtles reported) was incorporated to include the severity measure utilised by Shaver *et al.*, (2017). Employing severity categories to examine the relationship between environmental parameters was deemed the most appropriate approach as there was no way to determine the number of turtles within an area prior to an event. It is also important to note that there may be inconsistencies within STSSN stranding report records as the number of turtles reported would depend on the resources and personnel available during search efforts (personal communication, Dr. Donna Shaver (Texas Coordinator of the STSSN), September 2021). Preliminary analysis found green turtles (*Chelonia mydas*) were the species most affected by cold stun events, representing 99.77% of the affected population, and were therefore the selected species for further analysis.

Study Region

To establish a study region to assess environmental change in relation to hypothermic stunning season severity, the number of cold stunned green turtles per season per zone was assessed (Figure 1a, Figure 1b).

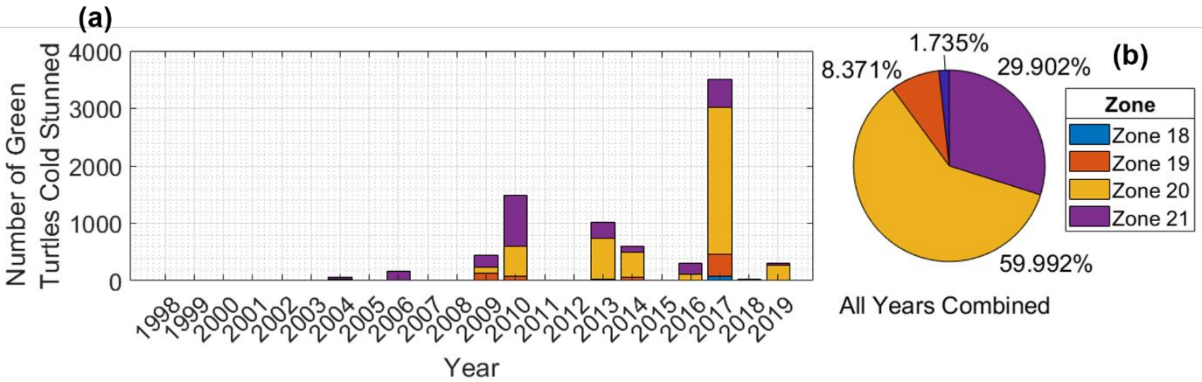

Figure 1: (a) Annual number of green turtles cold stunned per hypothermic stunning season per STSSN regional statistical zones 18 (blue), 19 (orange), 20 (yellow) and 21 (purple), representing the coastline of Texas State U.S (see Figure 2c); **(b)** Total number of green turtles cold stunned per STSSN regional statistical zones 18 (blue), 19 (orange), (blue), 19 (orange), 20 (yellow) and 21 (purple), representing the coastline of Texas State U.S (See Figure 2c). (Southeast Fisheries Science Center, 2022; MATLAB, 2022).

The greatest levels of hypothermia observed occurred within Zone 20. The majority of cold stunned individuals from this zone were found in Nueces (2,599 individuals) and Kleberg (1,831 individuals) counties which are representative of Corpus Christi Bay and Baffin Bay Texas, U.S.A. As Corpus Christi Bay represented the largest number of individuals affected by hypothermic stunning (2,602 turtles) it was selected as the study site. Due to Baffin Bay's relative proximity to Corpus Christi Bay (62.9 km) it is hoped the results obtained from this study are transferable to Baffin Bay, though this would require further analysis.

Corpus Christi Bay is one of seven major sandy beach bays found along the Texas coastline. The other major bays include Sabine Lake, Galveston, Matagorda, San Antonio, Aransas, and the Laguna Madre (Shaver *et al*., 2017). The bay is located on the central Texas coast (Figure 2b), connected by the Aranas Pass and Corpus Christi Pass to high energy nearshore waters of the north-western Gulf of Mexico (Figure 2a) (Morton and McGowen, 1980; Simms *et al*., 2008). Corpus Christi Bay has an average water depth of 3-4m and a <0.3m tidal range (Marmer, 1954; Shideler, 1984). It is connected to the shallower Nueces Bay tributary (~1m depth) (Figure 2a) which extends landward to the Nueces River which supplies the bay with freshwater and sediment (Simms *et al*., 2008; Yeager *et al*., 2006).

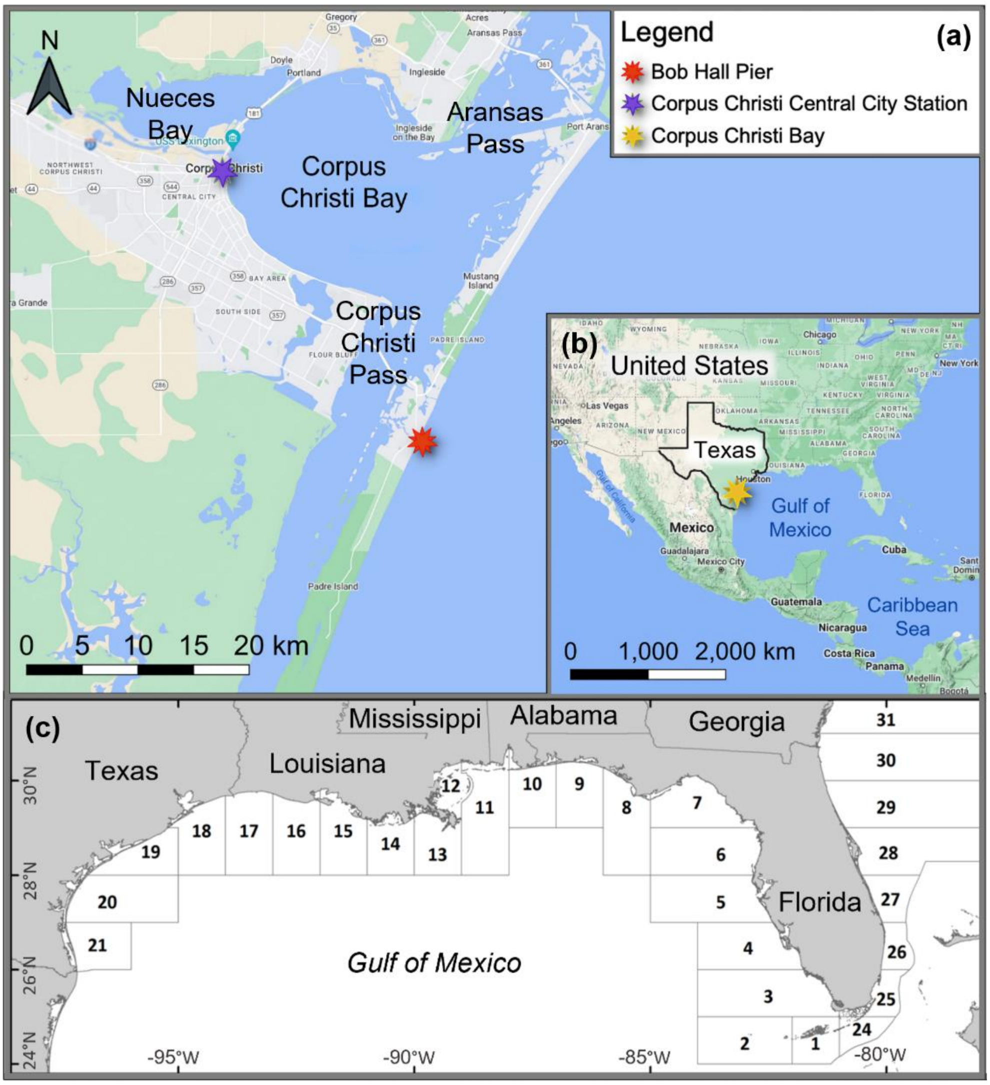

Figure 2: (a) Map of the Corpus Christi Bay study region indicating the location of the NOAA NOS station at Bob Hall Pier 27°34'51''N, 97°12'59''W (shown in red) (Conrad Blucher Institute, 2022) and Corpus Christi Central City Weather Station 27°47'52''N, 97°23'52''W (shown in purple) (World Weather Online, 2022) used as sources of environmental data; **(b)** location of Corpus Christi Bay, Texas (yellow) along the south-central coastline of the United States. Map generated using QGIS software (QGIS.org, 2022); **(c)** location of the STSSN regional statistical zones for the U.S. Gulf of Mexico (NOAA Fisheries, 2021).

Shallow water temperatures decrease rapidly when exposed to cold fronts; *Chelonia mydas* possibly become trapped in shallow inlets and bays such as Copus Christi Bay whist trying to travel southward when water temperatures cool (Foley *et al*., 2007; Roberts *et al*., 2013). Corpus Christi climate is semiarid (Thornthwaite, 1948), receiving 68-89 cm/year of precipitation with evaporation exceeding precipitation by 16-

20cm/year (Carr, 1967; Simms *et al*., 2008; White *et al*., 1983). The predominant wind direction is from the southeast (Lohse, 1956), however winter storms can bring winds from the north (Morton and McGowen, 1980; Shideler, 1984; Simms *et al*., 2008).

Environmental Data

In situ sea surface temperature (°C), air temperature (°C), wind speed (m/s) and wind direction (° from North) data were acquired from the National Oceanic and Atmospheric Administration (NOAA) National Oceanic Service (NOS) station at Bob Hall Pier (Conrad Blucher Institute, 2022) (Figure 2a). The station was selected as the it had the greatest data availability compared to other stations with similar proximity to Corpus Christi Bay, with measurements available at 30-minute intervals from September 2004 to present. For each category of severity, a hypothermic stunning season was selected for analysis based on data availability (low: 2012-2013, moderate: 2009-2010, high: 2014-2015, severe: 2017-2018) (Table 1). Air and surface water temperature were included as raw measurements as prolonged exposure to peaks/extreme values was important in determining if a green turtle becomes cold stunned. Wind speed and direction were incorporated into analysis as 24-hour average values. Additionally, daily historical pressure (mb) records were obtained from the Corpus Christi Central City Weather Station (Figure 2a) for the duration of each selected season for further weather analysis, with data being available from January 2009 (World Weather Online, 2022).

Table 1: Length of Hypothermic stunning season (days) across the full study period (1998-2019) for Corpus Christi Bay Texas U.S, showing the number of green turtles cold stunned per season and the corresponding magnitude of severity of the cold stun season in accordance with Roberts et al., (2013) and Shaver et al., (2017). Highlighted years indicate the selected hypothermic seasons chosen for further analysis and their severity rating (low 2012-2013 (green), moderate: 2009-2010 (yellow), high: 2014-2015 (orange), severe: 2017-2018 (red)).

Year (Start of Season)	Length of Hypothermic Season (Days)	Number of Green Turtles Cold Stunned	Category of Severity	Year (Start of Season)	Length of Hypothermic Season (Days)	Number of Green Turtles Cold Stunned	Category of Severity
1998	1	1	Low	2009	21	79	Moderate
1999	1	1	Low	2010	18	278	High
2000	0	0	Low	2011	0	0	Low
2001	2	2	Low	2012	8	10	Low
2002	0	0	Low	2013	51	333	High
2003	0	0	Low	2014	38	235	High
2004	0	0	Low	2015	4	5	Low
2005	0	0	Low	2016	9	78	Moderate
2006	5	7	Low	2017	34	1317	Severe
2007	0	0	Low	2018	3	19	Low
2008	0	0	Low	2019	6	237	High

Environmental parameters (water temperature, air temperature, pressure, wind data) for the duration of each selected hypothermic season were depicted on graphs generated using Matlab software (MATLAB, 2022) (Figure 3). Wind direction was shown using arrows plotted beneath wind speeds. The 10°C threshold was included to indicate how far and for how long water temperature fell below this value and was compared to a bar graph depicting the daily number of stunned individuals for Corpus

Christi Bay from the STSSN dataset (Figure 3). Additionally, measurements one week prior and after events were included for comparison. The graphs generated were evaluated to determine why certain hypothermic stunning seasons have greater magnitudes in accordance with Roberts *et al.*, (2013).

Lastly, the relationship between monthly mean sea surface temperatures at Bob Hall Pier and broader climate fluctuations was assessed by correlating water temperatures to the Southern Oscillation Index (SOI) (NOAA National Centres for Environmental Information (a), 2022), North Atlantic Oscillation (NAO) (NOAA National Centres for Environmental Information (b), 2022), Pacific Decadal Oscillation (PDO) (NOAA Earth System Research Laboratories, 2022), Artic Oscillation (AO) (NOAA Climate.gov Media, 2022) and Atlantic Multi-decadal Oscillation (AMO) (NOAA Physical Science Laboratory, 2022) climatic indexes.

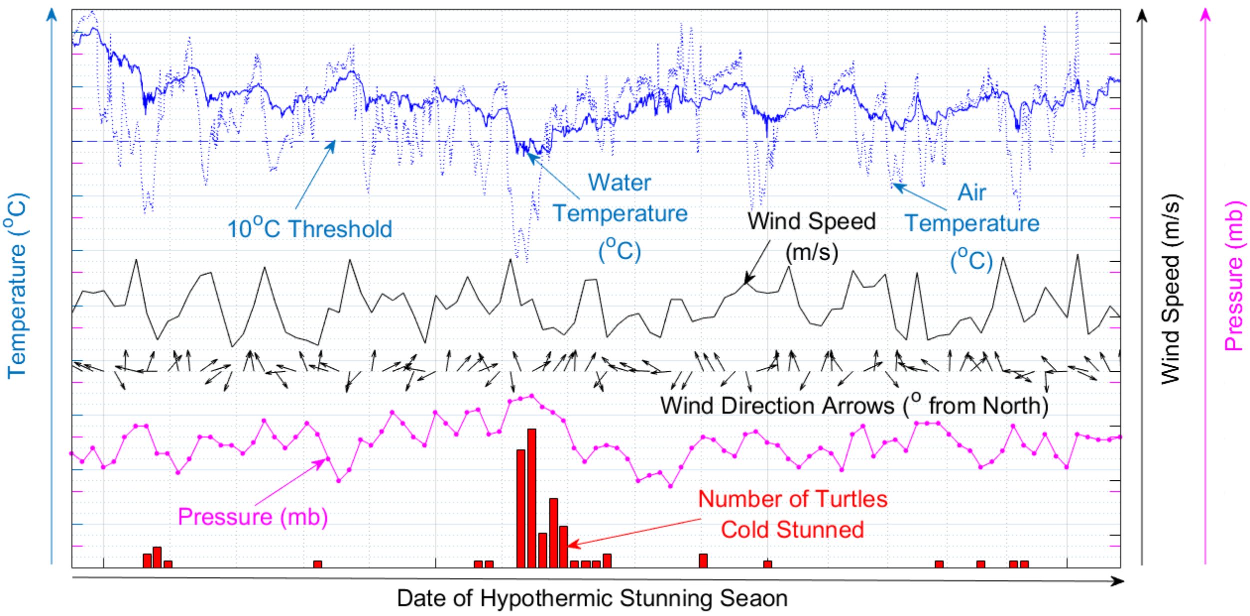

Figure 3: Example plot demonstrating how cold stun results (red bar chart) have been displayed with corresponding environmental parameters including water temperature (°C) (solid blue line), air temperature (°C) (dotted blue line), the 10°C water temperature threshold value (dashed blue line), pressure (mb) (pink line), wind speed (m/s) (solid black line) and wind direction (° from North) (black arrows). Graph produced using MATLAB Software (MATLAB, 2022).

Results

Sea Turtle Analysis

Hypothermic stunning was the largest cause of green turtle strandings in Texas between 1998 and 2019 (Figure 4a, Figure 4b). Of the 9,256 individuals stranded, 7,956 (85.96%) were attributed to cold stunning with 1,025 (11.07%) stranded from other causes and 275 (2.97%) incidentally captured (Figure 4b). The number of cold stunned green turtles increased exponentially over the study period (R^2 = 0.2037, p = 0.035) (Figure 4a). From Texas cold stun reports, 2,602 (30.70%) individuals were found within Corpus Christi Bay with four high/severe events occurring over the study period (winters of 2010-2011, 2013-2014, 2014-2015, and 2017-2018). 2,364 (90.85%) cold stunned turtles within Corpus Christi were found alive with 238 (9.15%) individuals reported dead (Figure 4c, Figure 4d). 98.35% of individuals found alive were found inshore (Figure 4c, Figure 4d) with circa sixty times more hypothermic turtles found inshore (2558 individuals, 98.31%) compared to offshore (44 individuals, 1.69%) (Figure 4c, Figure 4d). Of the green turtles found offshore, 39 (88.64%) were found alive (Figure 4c, Figure 4d).

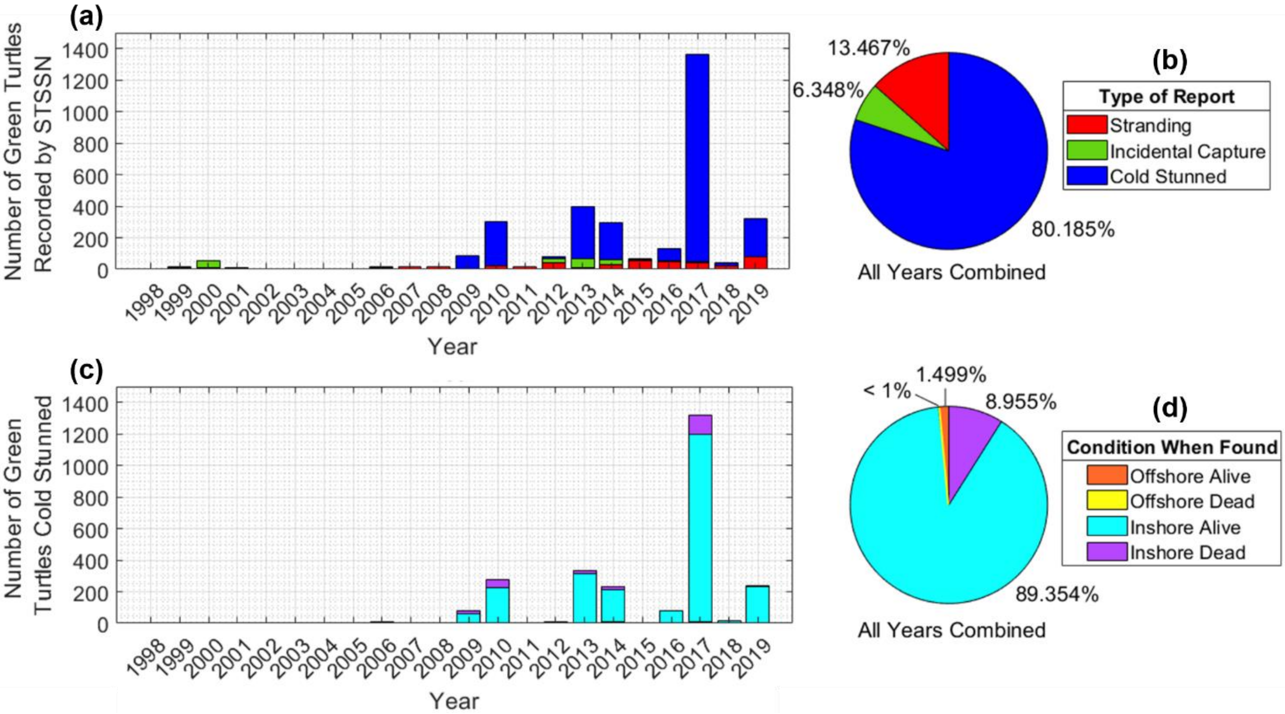

Figure 4: (a) Annual number of green turtles recorded in Texas U.S by the STSSN as stranded (red), incidentally captured (green) or cold stunned (blue) for the duration of the study period (1998-2019), **(b)** Percentage of green turtles recorded in Texas U.S by the STSSN as stranded (red), incidentally captured (green) or cold stunned (blue) across the entire study period (1998-2019), **(c)** Annual number of cold stunned green turtles in Texas U.S recorded by the STSSN found offshore and alive (orange), offshore and dead (yellow), inshore and alive (cyan) or inshore and dead (purple), **(d)** Percentage of cold stunned green turtles recorded in Texas U.S by the STSSN found offshore and alive (orange), offshore and dead (yellow), inshore and alive (cyan) or inshore and dead (purple) across the entire study period (1998-2019). (Southeast Fisheries Science Centre, 2022; MATLAB, 2022).

Environmental Parameter Analysis

Hypothermic season duration within Corpus Christi Bay ranged from 2 days (1998-1999, 2000-2001) to 53 days (2013-2014) with a mean (μ) duration of 10.05 days (standard deviation (σ) = 14.48 days, n = 22) (Table 1). Season duration is positively correlated to the number of cold stunned turtles reported ($R^2 = 0.4099$, $p = 0.0013$) but not correlated to the percentage of these turtles found alive ($R^2 = 0.0092$, $p = 0.74$). To assess the relationship between environmental parameter change and hypothermic season severity, a winter from each category of severity: low (2012-2013), moderate (2009-2010), high (2014-2015) and severe (2017-2018) were selected based on data availability for further analysis (Table 1). For all years and severity levels cold stunning only occurred during the hypothermic stunning season (November-March), but the number of cold stunned individuals peaked at different times per winter depending on the passage of severe weather systems. At the start of an event the majority of individuals were found alive, a greater percentage of turtles were found dead as the duration of the event increased.

For all severity levels, multiple cold stunning events were established per hypothermic season. In accordance with Shaver *et al.*, (2017), cold stunnings were attributed to the same event if they were separated by 2 days or less. For all events, changes to air temperature and pressure were observed to proceed and drive changes in Corpus Christi Bay sea surface temperature. Across the study period, there were no instances where sea surface temperature dropped below 10°C without reports of hypothermic stunning. For easiest comparison, hypothermic stunning seasons were assessed in order of severity.

2012-2013 Hypothermic Stunning Season: Low Severity
The lowest severity season occurred from 29/12/2012-18/01/2013 with 10 individuals cold stunned (Figure 5). Sudden drops in air temperature below 10°C were observed in the 2 days preceding cold stun reports in nine out of ten cases, with a minimum temperature of 3°C (μ = 14.47°C) recorded on 26/12/2012 (Figure 5). Sudden changes to air temperature were accompanied by surface pressure changes. Pressure decreases to circa 1014mb before increasing to 1027-1030mb when the cold stunned turtles are reported (Figure 5).

Wind speed and direction fluctuate naturally (μ = 5.871m/s), with a minimum/maximum recorded wind speed of 2.75/11.20m/s (Figure 5). There is no correlation between wind speed or direction with the number of cold stunned turtles (R^2 = 0.0009, p = 0.89) but wind speed appeared to increase with decreased barometric pressure. The water temperature also failed to drop below the 10°C threshold value, which may give justification to the low season severity.

2009-2010 Hypothermic Stunning Season: Moderate Severity
Using the same severity categories for events as per season, the 2009-2010 hypothermic season was composed of a low severity event (05/12/2009-07/12/2009) affecting 6 green turtles and a secondary moderate event (05/01/2010-16/01/2010) causing 65 cases of cold stunning (Figure 6). Concurring with the 2012-2013 season, hypothermic stunnings occur in the days following sharp drops in air temperature, however the minimum temperature was greater for the 2009-2010 season, with a low of -1.1°C recorded on 10/01/2010 (μ = 12.49°C) (Figure 6). Although surface pressure appears to fluctuate naturally, before each event pressure decreased by 5-10mb from around 1015mb and then spiked simultaneously with sudden drops in air temperature (Figure 6). The low severity event saw a smaller spike in air pressure (1024mb) compared to the moderate event (1035mb).

Wind speed and direction were not significantly correlated to the number of cold stun reports (R^2 = 0.029, p = 0.43), although wind speeds seemed to increase with pressure decrease. Additionally, the dominant wind direction was from the south/south-east, which reversed producing northerly winds with sudden declines in air temperature (Figure 6). Sea surface temperature reduced below the 10°C threshold between 08/01/2010-12/01/2010, reaching an 8.6°C minimum, accompanying surface air temperatures below 0°C (Figure 6). The majority (65.82%) of cold stunned turtles were found during times where sea surface temperature dropped below 10°C.

2014-2015 Hypothermic Stunning Season: High Severity
The 2014-2015 high severity winter was comprised of two moderate cold stunning events occurring from 13/11/2014-26/11/2014 and 03/01/2015-26/01/2015 affecting

66 and 160 individuals retrospectively (Figure 7). Again, hypothermic reports were correlated to abrupt air temperature decreases frequently below 5°C, reaching a minimum of 2.1°C (μ = 13.97°C) (Figure 7). Surface pressure descends by approximately 10mb to 1012-1016mb one to two days prior to the first cold stun cases. Both events saw pressures spike above 1030mb with the larger event presenting higher surface pressure (1035mb) (Figure 7).

Reflecting the 2009-2010 event there was no significant correlation between wind speed and direction and the number of hypothermic turtles (R^2 = 0.016, p = 0.37). Yet a similar reversal in wind direction from the south/south-east to the north/north-west with spikes in frigid air temperature was observed and wind speeds reflected the inverse of pressure changes (Figure 7). The larger and later of the two events coincided with sea surface temperature values dropping below 10°C between 11/01/2015-12/01/2015 and again from 14/01/2015-16/01/2015 corresponding to peaks of cold stun reports during the second event (Figure 7). Although the minimum temperature recorded was 3.2°C higher than the 2009-2010 event, the temperature dropped more frequently and for longer suggesting length and frequency of exposure may contribute to the number of hypothermic stunnings.

2017-2018 Hypothermic Stunning Season: Categorised Severe

The highest severity hypothermic stunning season occurred between 2017-2018. The winter of 2017-2018 was composed of a moderate severity event between 08/12/2017-18/12/2017 with 109 green turtles reported cold stunned followed by a severe cold stun event 13 days later (01/01/2018-31/01/2018) with 1,206 individuals recorded (Figure 8). The combined effect of two substantial events resulted in the hypothermic stunning of 1,315 individuals, accounting for circa 50% of the total number of turtles cold stunned within Corpus Christi Bay between 1998-2019.

There were three main occasions where surface air temperature dropped substantially reaching temperatures 0.9°C to -2°C, the minimum recorded value for the study period (μ = 13.77°C), which correlate to peaks of cold stun reports with a circa 24-hour lag (Figure 8). Rapid reduction in air temperature reflected patterns of surface pressure increase. Peaks in surface pressure of 1036mb and 1039mb are observed on 01/01/2018 and 17/01/2018 correlating to 1-2 days prior to the highest cold stun reports (Figure 8). Between peaks, surface pressure decreases rapidly by 25mb to 1011mb before increasing abruptly back to 1039mb.

Concurrent with all severity categories there was no significant relationship between wind speed or direction and the number of hypothermic stunnings (R^2 = 0.0018, p = 0.78) but wind direction reversal from the south/south-east to the north/north-west with sudden decreases in air temperature was observed with wind speed spiking with barometric pressure decreases (Figure 8). During the severe event sea surface temperature dropped twice below the 10°C threshold, for 3 (03/01/2018-05/01/2018) and 5 days (17/01/2018-21/01/2018), reaching a minimum 7.9°C (Figure 8) which was the lowest recorded temperature for the duration of the study.

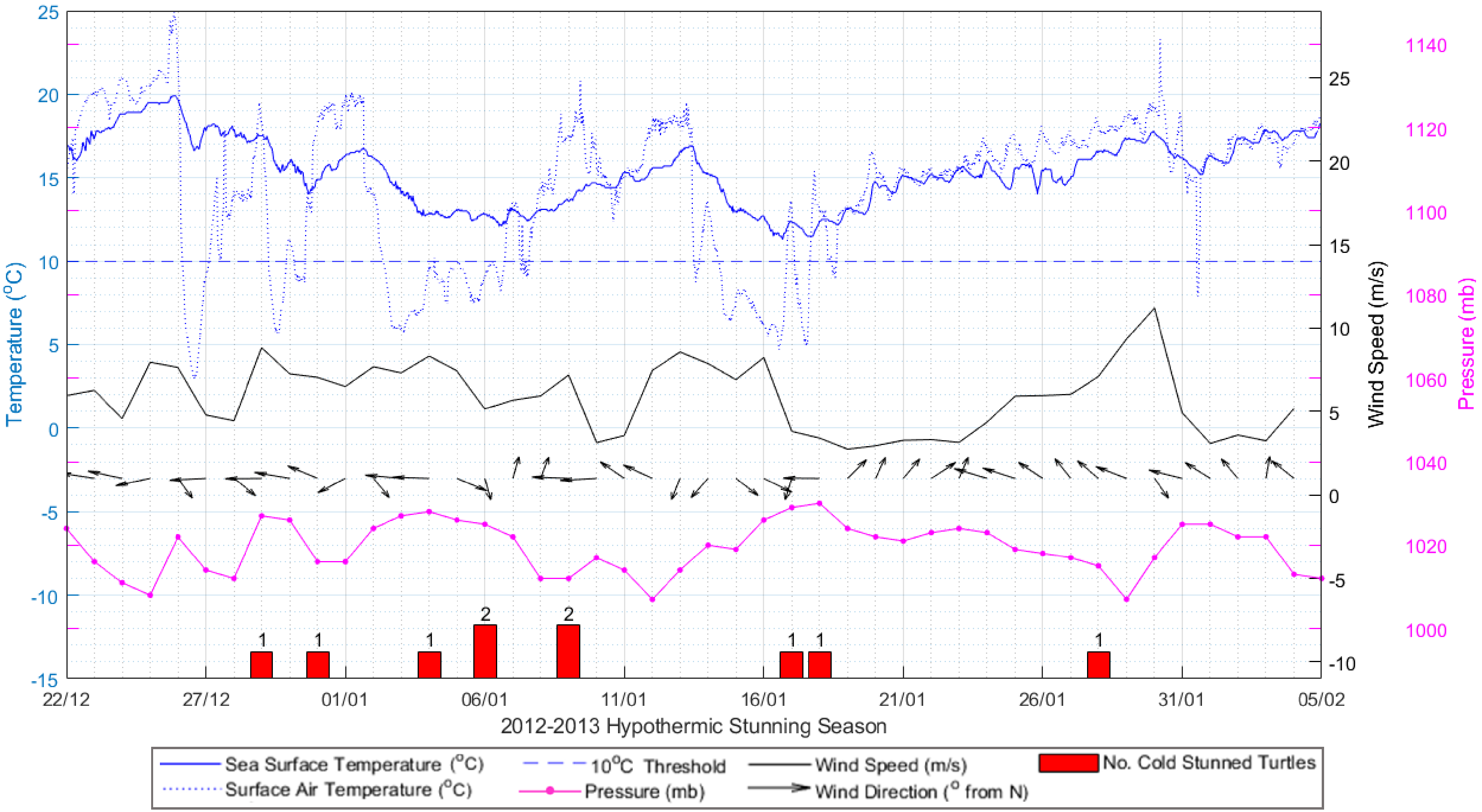

Figure 5: Corpus Christi Bay hypothermic stunning season 2012-2013 (low severity) showing sea surface temperature (°C) (blue solid line), air temperature (°C) (blue dotted line), and 10°C threshold value (blue dashed line), surface air pressure (mb) (magenta line), wind speed (m/s) (black line) and wind direction (° from North) (black arrows), alongside the daily number of cold stunned green turtles recorded (red bars) (Conrad Blucher Institute, 2022; World Weather Online, 2022; Southeast Fisheries Science Center, 2022). Graph produced using Matlab Software (MATLAB, 2022)

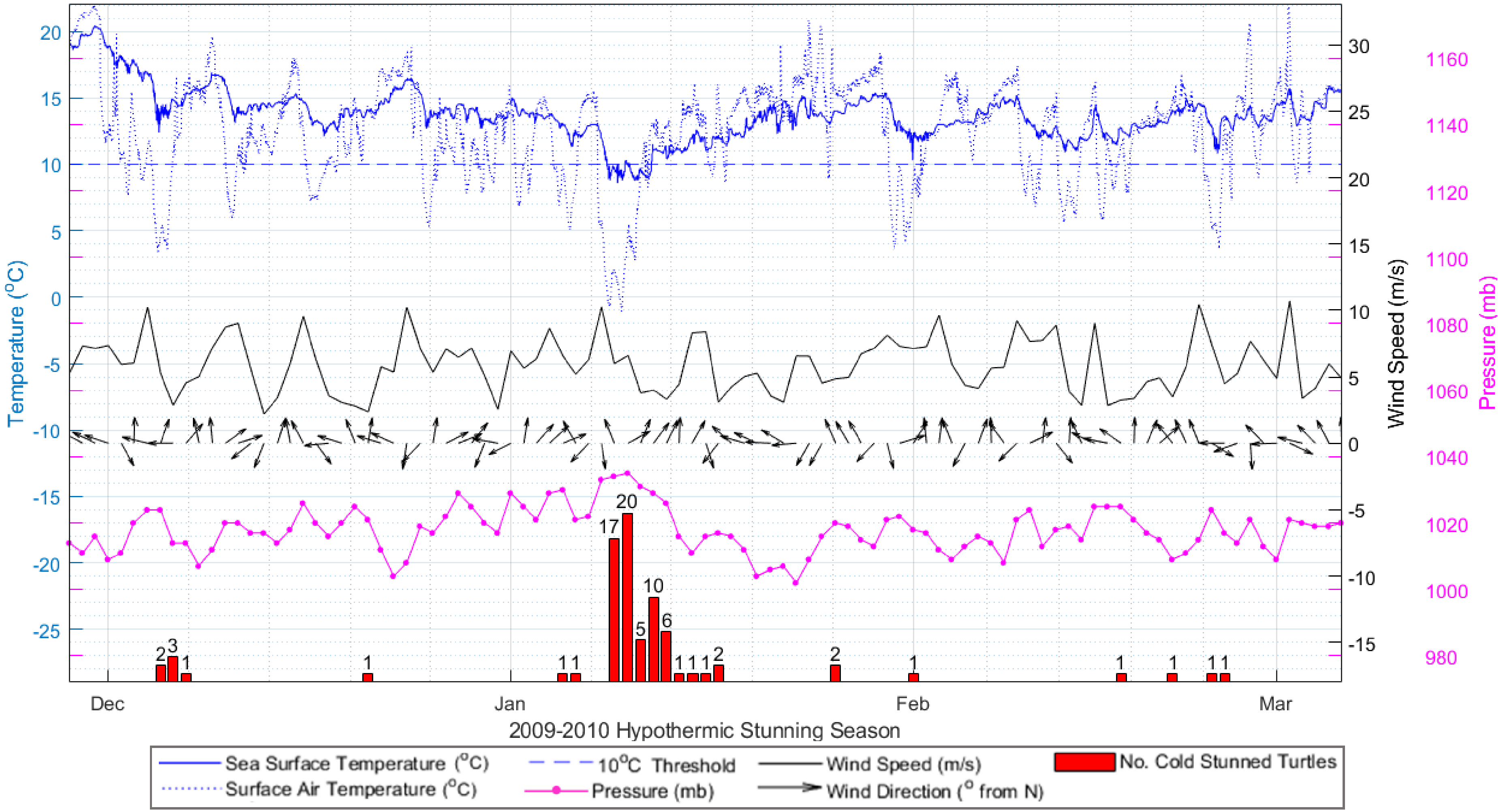

Figure 6: Corpus Christi Bay hypothermic stunning season 2009-2010 (moderate severity) showing sea surface temperature (°C) (blue solid line), air temperature (°C) (blue dotted line), and 10°C threshold value (blue dashed line), surface air pressure (mb) (magenta line), wind speed (m/s) (black line) and wind direction (° from North) (black arrows), alongside the daily number of cold stunned green turtles recorded (red bars) (Conrad Blucher Institute, 2022; World Weather Online, 2022; Southeast Fisheries Science Center, 2022). Graph produced using Matlab Software (MATLAB, 2022)

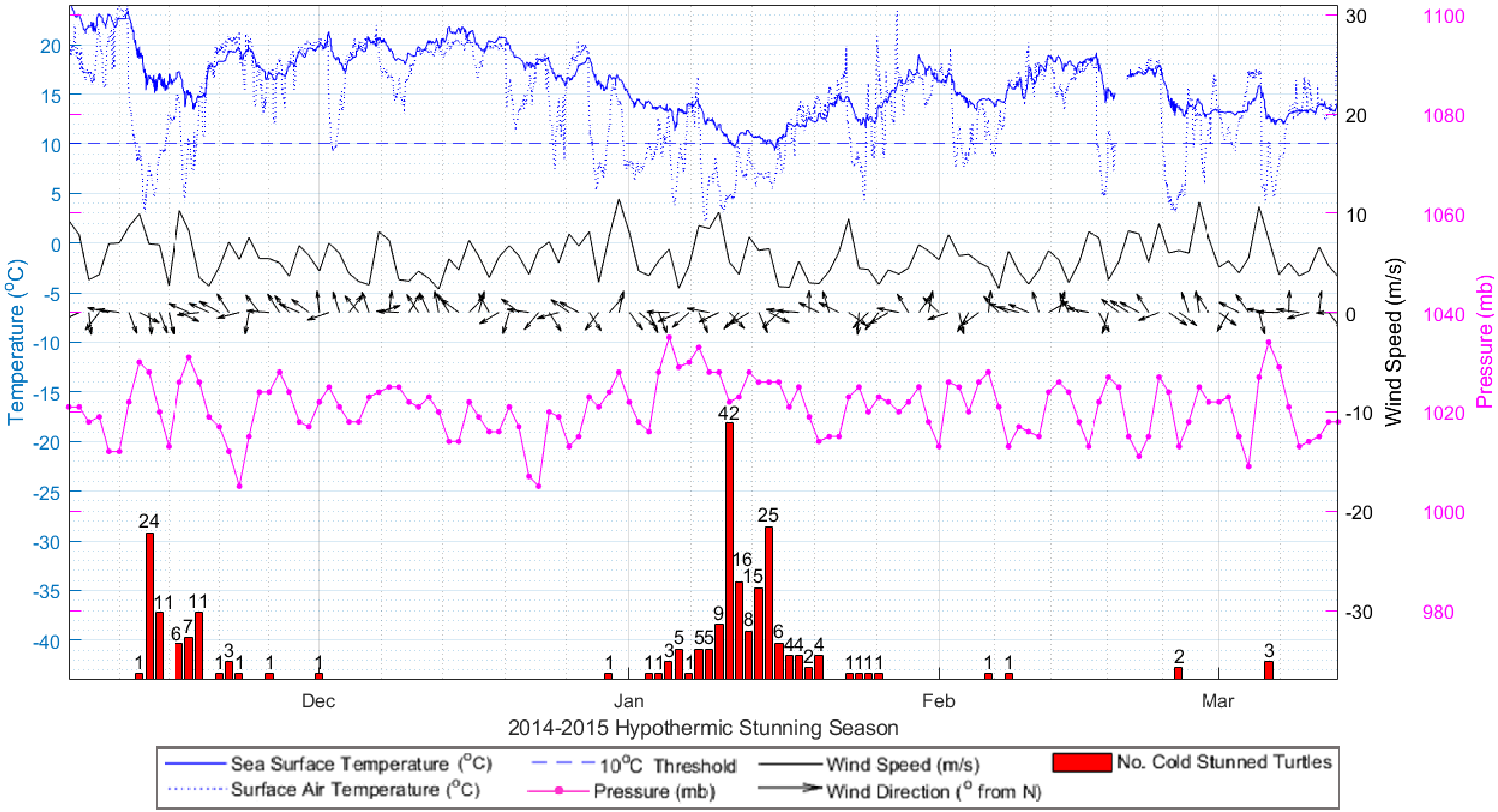

Figure 7: Corpus Christi Bay hypothermic stunning season 2014-2015 (high severity) showing sea surface temperature (°C) (blue solid line), air temperature (°C) (blue dotted line), and 10°C threshold value (blue dashed line), surface air pressure (mb) (magenta line), wind speed (m/s) (black line) and wind direction (° from North) (black arrows), alongside the daily number of cold stunned green turtles recorded (red bars) (Conrad Blucher Institute, 2022; World Weather Online, 2022; Southeast Fisheries Science Center, 2022). Graph produced using Matlab Software (MATLAB, 2022).

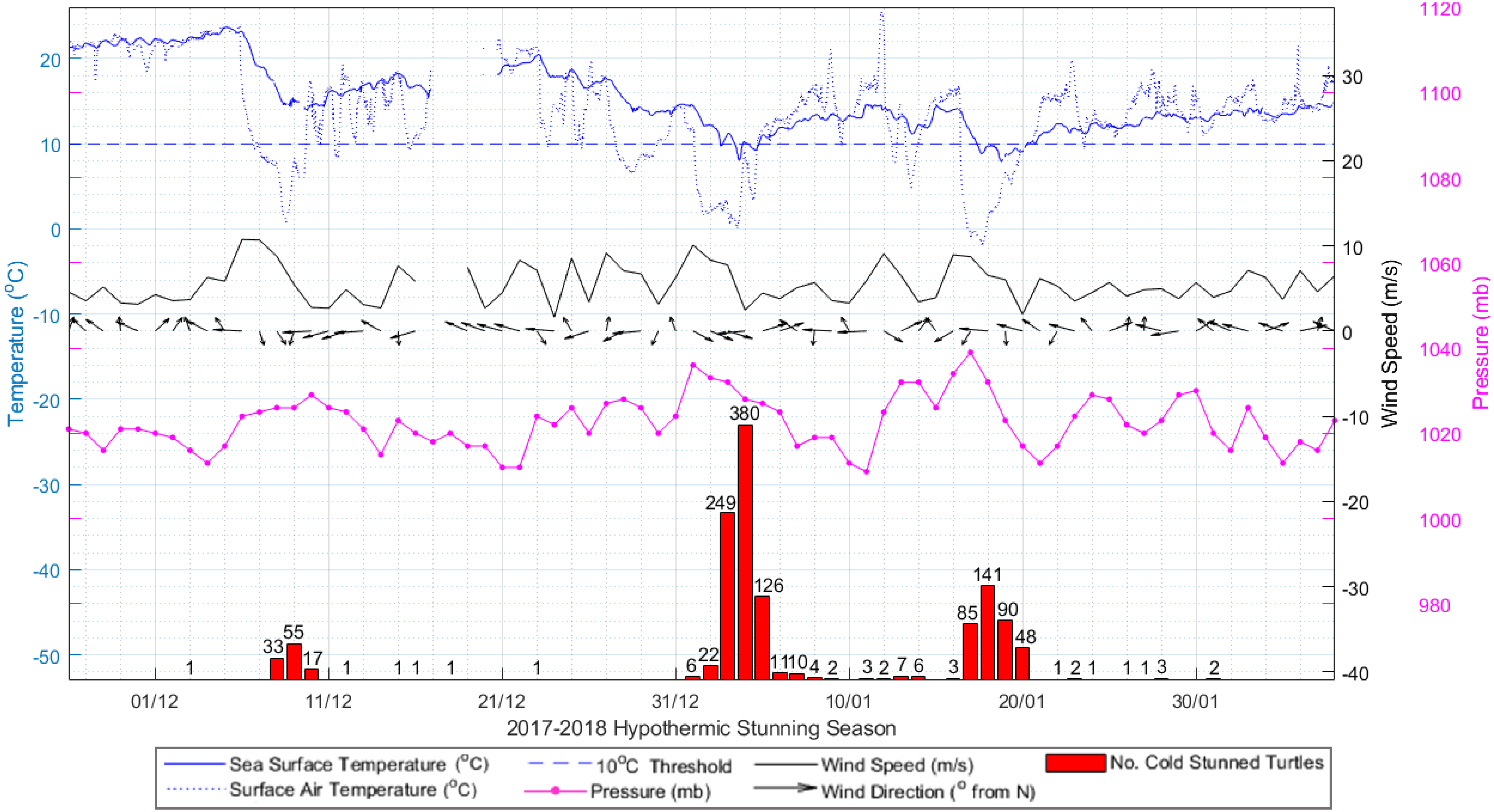

Figure 8: Corpus Christi Bay hypothermic stunning season 2017-2018 (categorised severe) showing sea surface temperature (°C) (blue solid line), air temperature (°C) (blue dotted line), and 10°C threshold value (blue dashed line), surface air pressure (mb) (magenta line), wind speed (m/s) (black line) and wind direction (° from North) (black arrows), alongside the daily number of cold stunned green turtles recorded (red bars) (Conrad Blucher Institute, 2022; World Weather Online, 2022; Southeast Fisheries Science Center, 2022). Graph produced using Matlab Software (MATLAB, 2022).

Climate Index Analysis

Monthly mean values of sea surface temperature were compared with Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indexes to assess the wider climatic influences on producing a cold stun event. Sea surface temperatures taken from Bob Hall Pier were not significantly correlated to the SOI ($R^2 = 0.0035$, $p = 0.44$), PDO ($R^2 = 0.0132$, $p = 0.14$) or AO ($R^2 = 0.0023$, $p = 0.52$) but presented statistically significant correlation to the AMO ($R^2 = 0.2415$, $p < 0.00001$) and NAO ($R^2 = 0.0659$, $p = 0.00076$) indexes. Hence, changes to AMO and NAO and therefore larger scale climate variability may contribute to the severity of a hypothermic stunning season.

Discussion

Hypothermic stunning events within Corpus Christi were the leading cause of green turtle (*Chelonia mydas*) strandings between 1998-2019 according to the STSSN network. The severity of a hypothermic stunning season varied in response to environmental change. Changes to water temperature, air temperature and surface air pressure parameters were observed to measurably influence the reported number of cold stun cases and therefore control the threat posed by hypothermic seasons or individual events.

Temporal Trends

The number of juvenile green turtles within Texas waters documented by the STSSN from 1998-2019 increased exponentially. Possibly this is due to increased public awareness of stranding reports and additional funding allowing improvements to STSSN search and rescue efforts (Shaver, 1998; Shaver *et al*., 2017), but may also be attributed to increased juvenile abundance due to enhanced recruitment from Gulf of Mexico natal beaches (Shamblin *et al*., 2017; Shaver *et al*., 2017). Corpus Christi Bay and surrounding regions documented the highest levels of hypothermic stunning, however the STSSN considers these minimum estimates (Shaver *et al*., 2017; Teas, 1993) as stranded turtles can go undetected especially in areas that are less developed or harder to access (personal communication, Benjamin Higgins (STSSN Data Steward), August 2021). Additionally, the number of deceased turtles reported is likely to be an underestimate as only a fraction of dead turtles wash ashore and some turtles that were taken for rehabilitation would not have survived (Shaver *et al*., 2017). The passive drifting of cold stunned, injured or dead turtles may also impact spatial trends as individuals could drift from their original location with winds and currents (Shaver *et al*., 2017). These factors should be considered as limitations of this research.

Without human intervention, hypothermic stunning events can cause substantial mortality of juvenile green turtles within Corpus Christi and surrounding waters. Turtles found quickly through targeted search and rescue efforts are more likely to survive than individuals found days into the start of the event (Shaver *et al*., 2017; Witherington and Ehrhart, 1989) supported by an increased mortality with progression of hypothermic stunning events observed in this study. As annual average temperatures decrease during winter, many turtle populations emigrate from temperate areas to warmer tropical waters (Shaver *et al*., 2017; Witherington and Ehrhart, 1989). In Texas, this supports the movement of individuals offshore or southward inshore toward Corpus Christi Bay and other shallow inlet/bay areas of the Laguna Madre

(Shaver *et al*., 2017). Green turtles that remain in this area are especially vulnerable as the temperature of shallow waters can decrease rapidly and there are only four limited passes (Aransas Pass, Packery Channel, Mansfield Channel, Brazos Santiago Pass) to warmer Gulf of Mexico waters causing individuals to come trapped and subjected to hypothermic stunning (Foley *et al*., 2007; Mendonça, 1981; Mendonça, 1983; Roberts *et al*., 2013; Shaver *et al*., 2017). This gives justification to the significantly greater number of turtles found hypothermic inshore (2,558 individuals) than offshore (44 individuals) where waters are deeper.

Environmental Conditions Controlling Cold Stun Events

Environmental parameters such as barometric pressure, air temperature, wind speed and wind direction are known to influence hypothermic stunning events by causing changes to sea surface temperature (Roberts *et al*., 2013; Shaver *et al*., 2017; Still *et al*., 2005). The results from this study are concurrent with conclusions drawn by Shaver *et al.*, (2017) and Roberts *et al.*, (2013) who found atmospheric variables influenced oceanographic parameters which as a consequence were a direct cause of juvenile *Chelonia mydas* hypothermia.

All cold stun events from associated winters of the 2009-2010, 2012-2013, 2014-2015 and 2017-2018 hypothermic stunning seasons were recorded during or just after the passage of a cold front. This is concurrent with studies by Shaver *et al.*, (2017) who reported 99% of all hypothermic cases to be as a result of the passage of a cold front. For example, the movement of a cold front over Nueces county Texas is observed on 07/01/2010 (Figure 9) at the beginning of the seasons moderate event, a couple of days prior to the daily peak in cold stunned turtles reported for the 2009-2010 season (see Figure 6). A cold front also passes over Corpus Christi Bay between from the 11/11/2014-12/11/2014 (see Appendix A, Figures A2 and A3), the day before cold stun reports of the first event of the 2014-2015 hypothermic stunning season. Even during the low severity hypothermic season (2012-2013) the passing of cold fronts still precedes cold stun reports (see Appendix A, Figure A1).

Shaver *et al.*, (2017) also stated additional cold fronts can prolong an events duration, which was reflected in this study with multiple fronts passing per events/seasons with longer durations and higher severity. For instance, during the severe event of the 2017-2018 hypothermic stunning season (01/01/2018-31-01/2018) a cold front passes over Corpus Christi the day before the start of the event (31/12/2017); a secondary cold front then hits the area as sea surface temperatures begin to recover (16/01/2018) prolonging the event and increasing its severity (see Appendix A, Figures A4 and A5).

With the passing of the cold front air temperature becomes more frigid which in turn decreases sea surface temperature, resulting in the rapid cooling of shallow water passes and bays such as Corpus Christi (Climate and Weather, 2020). Across the study period, the movement of cold fronts were associated with a decrease in barometric pressure as the front approaches before pressure increases suddenly as the cooler, denser air replaces the lifting of warm moist air (Climate and Weather, 2022). Although winds become slightly stronger for the first few days as the front passes and have been observed to change from a south-east to northward direction during storm conditions (Simms *et al*., 2008); cold stunned turtles are still recorded when the wind speed and direction revert as water temperatures have a delayed response time and take longer to recover (Shaver *et al*., 2017). This is therefore responsible for the correlation observed but the lack of significant relationship between the number of hypothermic green turtles and measured wind parameters.

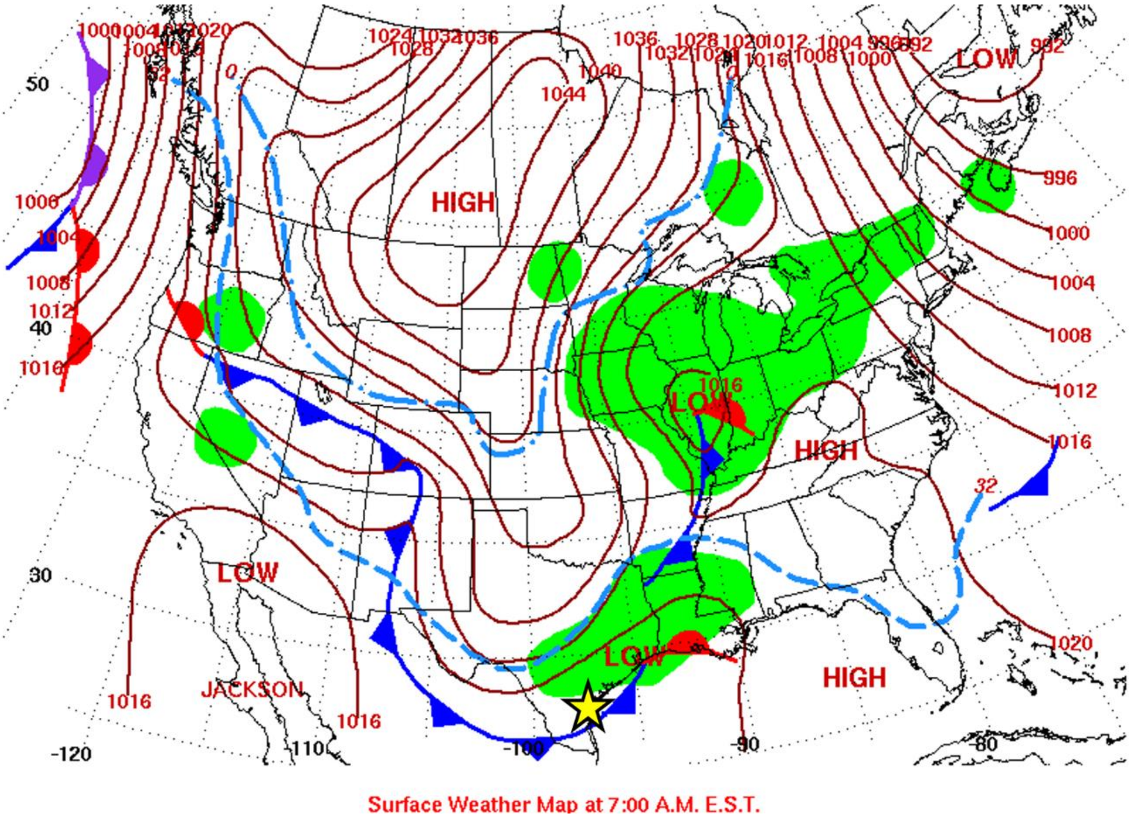

Figure 9: Daily U.S surface weather map for 07/01/2010 at 7:00 a.m. E.S.T showing the formation and progression of cold fronts (solid blue line with triangles) and warm fronts (solid red line with semi-circles) around regions of high (H) and low (L) pressure across the United States with resulting precipitation (green shaded regions) (NOAA Weather Prediction Center, 2022). The location of Corpus Christi Bay Texas is indicated by the yellow star marker.

There is a potential for continental scale climate fluctuations to predict particularly severe hypothermic stunning seasons. The strongest correlation was observed between sea surface temperature and the PDO and AMO indexes reflecting results found by both Shaver *et al.*, (2017) and Roberts *et al.*, (2013). Results from this study show that hypothermic season severity in Corpus Christi Bay was not necessarily attributed to large fluctuations of the PDO or AMO indexes, possibly due to the large periodicity of the PDO and AMO cycles which outrun the study period, but this would require additional research.

Predicting Cold Stunning Events

Previous studies have attributed cold stun events to sea surface temperature declines below 10°C, suggesting days of hypothermic stunning are predictable by assessing when water temperature drops below this threshold. Although this study and previous research conducted by Schwartz (1978) and Roberts *et al.*, (2013) prove this to be the case, using sea surface temperature alone does not serve as a good predictor of cold stunning. For the hypothermic stunning seasons 2009-2019 (based on data availability), using a threshold sea surface temperature of 10°C highlighted the cold stunning days of 1,255 out of 2,590 green turtles, representing less than half (48.46%) of individuals affected. When using the same value to predict hypothermic stunning 24-hours in advance, the days associated with 954 cold stunned turtles (36.83%) were predicted. Hence, using a 10°C sea surface temperature threshold to predict cold stun events is highly inaccurate and when accurate predicted days correlated to cold stun reports, which does not allow adequate time for preparation of search and rescue efforts by the STSSN or similar organisations.

Instead, this study suggests using changes to atmospheric parameters to predict cold stunning events through highlighting the formation and progression of cold fronts over Corpus Christi. To assess this, a Matlab model was generated using data acquired from Bob Hall Pier, Corpus Christi Central Station and the STSSN to test the accuracy of an in advance prediction method at highlighting dates of reported hypothermic stunning for the seasons 2009-2019 (based on data availability).

Of the 2602 cold stunned cases across 201 days over the entire study period (1998-2019), 2590 individuals were recorded between 2009-2019 over 192 days. Therefore using the 2009-2019 hypothermic seasons was deemed a suitable representation of the study period, accounting for 99.53% of the total population of cold stunned turtles examined. As no turtles were reported cold stunned outside of a hypothermic stunning season, all versions of the model only predict dates within the hypothermic season (1st November - 31st March). Half hourly measurements from Bob Hall Pier were converted to daily means used alongside daily pressure values and cold stun records.

Firstly, wind direction data was analysed through the model as this study supported by research by Simms *et al.*, (2008) indicated a change in wind direction from south-easterlies to northerlies (135-224° from N) occurred during storm conditions which may highlight the formation of cold fronts and therefore predict cold stun events. Similar to applying a 10°C water temperature threshold, wind direction variation was a poor predictor of hypothermic stunning and was more accurate at predicting days when cold stunning occurred (860 turtles, 33.20%), than predicting days of cold stunning 1-day in advance (452 turtles, 17.45%). Additionally, 542 false predictions occurred over the study period; this was attributed to wind reversal occurring during storm conditions and not specifically movement of cold weather frontal systems. Therefore warmer storms would cause a similar shift in wind direction but without significantly cooling sea surface temperatures and therefore not affect green turtle populations.

Across all severity levels, sudden drops in air temperature appeared to be the most correlated parameter to the number of green turtles affected and consequently influential in predicting hypothermic stunning events. To evaluate this, the same 10°C temperature threshold used for water temperature was applied as a maximum air temperature threshold. Contradictory to the previous parameters examined, the air temperature threshold was more accurate at predicting cold stunned turtles one-day in advance (2,080 turtles, 80.30%) than on the day where turtles were recorded cold stunned (1,959 turtles, 75.64%). This suggests air temperature has the potential to accurately predict cold stun events, however there were 63 false predictions which may waste personnel and resources if used alone as a prediction method.

To reduce the number of false predictions and coincide with measurements observed as a cold front passes over Corpus Christi Bay, an additional minimum

1020mb surface pressure threshold was added to the maximum 10°C air temperature threshold value in a combined conceptual model.

To summarise, to provide a one-day in advance prediction of cold stunning, the model highlighted dates between 2009-2019 which met the following conditions:

1) The date must lie within a hypothermic stunning season (1st November-31st March)
1) The air temperature ≤10°C
2) The surface air pressure is ≥ 1020mb

When historical data (2009-2019) was fed into these statements the model successfully predicted the cold stunning of 2,240 individuals (86.49%). Using the date predicted by the model to mark the start of a hypothermic event, rather than highlighting individual days of hypothermic stunning, increased this value to 2,531 green turtles or 97.72% of the total number of turtles cold stunned over this period, accounting for 192 of the total 235 (81.70%) cold stun days. The model did generate 31 false predictions; however this is less than half (49.2%) the number of incorrect predictions made solely using a 10°C air temperature threshold and only accounts for 1.89% of the total days modelled (1,640 days total).

This model, with development, has possible management implications by providing an in advance prediction of cold stunning. As water temperature decreases as soon as air temperature decreases, a few hours could determine if conditions are tolerable or fatal for green turtle populations in shallow water environments (Roberts *et al*., 2013). Therefore preparing staff and equipment based on the development of cold fronts as a pre-emptive precautionary measure can help reduce green turtle mortality, allowing for better organisation during events and increased search and rescue efforts (Roberts *et al*., 2013).

Conclusions

Hypothermic stunning events were the leading cause of green turtle (*Chelonia mydas*) strandings within Corpus Christi between 1998-2019. Changes to atmospheric variables, most notably air temperature and surface air pressure, during the formation/progression of cold fronts over Corpus Christi Bay were observed to drive decreases in sea surface temperature which subsequently were a direct cause of juvenile *Chelonia mydas* hypothermia. Cold stun events with increased severity were attributed to increased frequency and duration of frigid sea surface temperature exposure in response to environmental change rather than how quickly water temperatures cooled.

This study supports findings by Schwartz (1978) that green turtles will become cold stunned at 10°C. However using this temperature as a sea surface threshold value to forecast hypothermic events is ineffective, as water temperature changes below 10°C correspond to dates of cold stun reports rather than providing an in advance prediction. Instead model results from this study suggest using a 10°C maximum air temperature threshold alongside a 1020mb surface pressure minimum threshold to predict dates of cold stunning within a hypothermic stunning season (1st November-31st March) 24-hours in advance, to coincide with measurements observed as a cold weather front passes over Corpus Christi Bay. This model was effective at predicting the cold stunning of 86.49% of individuals when highlighting distinct cold stun days or 97.72% of individuals when the days highlighted by the model were used as the start of hypothermic stunning events. These results suggest using the development and passage of cold weather fronts as an in advance prediction of events, improving response times and minimising the effect of cold stunning on green turtle populations.

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References

Balazs, G.H., 1999. Factors to consider in the tagging of sea turtles. Eckert KL Bjorndal KA Abreu-Grobois FA Donnelly M Ed. Res. Manag. Tech. Conserv. Sea Turt. Wash. DC IUCNSSC Mar. Turt. Spec. Group 101–109.

Brill, R.W., Balazs, G.H., Holland, K.N., Chang, R.K.C., Sullivan, S., George, J.C., 1995. Daily movements, habitat use, and submergence intervals of normal and tumour-bearing juvenile green turtles (Chelonia mydas L.) within a foraging area in the Hawaiian Islands. J Exp Mar Bio Ecol 203–2018.

Brongersma, L.D., 1982. Marine turtles of the eastern Atlantic Ocean. Bjorndal Keditor Biol. Conserv. Sea Turt. Wash. DC Smithson. Inst. Press 407–416.

Carr, J.T., 1967. The Climate and Physiography of Texas: Austin, Texas. Tex. Water Dev. Board Rep. 53, 27 p.

Climate and Weather, 2020. Characteristics of world weather and climate: Weather Fronts, https://www.climateandweather.net/world-weather/weather-fronts/. Accessed 26/03/2022.

Conrad Blucher Institute (CBI) for Surveying and Science Texas A&M University Corpus Christi, 2022. NOAA (National Oceanic and Atmospheric Administration) National Ocean Service station 014: Bob Hall Pier, data from 31/08/2004 – 01/01/2020, http://www.cbi.tamucc.edu/dnr/station/

Coyne, M.S., 1994. Feeding Ecology of Green Sea Turtles. MSc Thesis Tex. AM Univ. 88.

Davenport, J., 1997. Temperature and the life-history strategies of sea turtles. J Therm Biol 479–488.

Foley, A.M., Singel, K.E., Dutton, P.H., Summers, T.M., Redlow, A.E., Lessman, J., 2007. Characteristics of a Green Turtle (Chelonia mydas) Assemblage in Northwestern Florida Determined During a Hypothermic Stunning Event. Gulf Mex. Sci. 25. https://doi.org/10.18785/goms.2502.04

Lohse, E.A., 1956. Dynamic geology of the modern coastal region, northwesterm Gulf of Mexico in Hough, J.L., ed., Finding Ancient Shorelines: A Symposium with Discussions. Soc. Econ. Mineral. Paleontol. SEPM Spec. Publ. 3 99–104.

Lutz, P.L., Musick, J.A., 1997. The biology of sea turtles, CRC marine biology series. CRC Press, Boca Raton (FL.).

Marmer, H.A., 1954. Tides and sea level in the Gulf of Mexico, in Gulf of Mexico, Its Origin, Waters, and Marine Life. US Dep. Inter. Fish Wildl. Serv. Bull. 89, 101–118.

MATLAB, 2022. Version 9.10.0.1649659 (R2021a) Update 1, Natick, Massachusetts: The MathWorks Inc.

Mendonca, M.T., 1981. Comparative Growth Rates of Wild Immature Chelonia mydas and Caretta caretta in Florida. J. Herpetol. 15, 444-447. https://doi.org/10.2307/1563536

Mendonça, M.T., 1983. Movements and Feeding Ecology of Immature Green Turtles (Chelonia mydas) in a Florida Lagoon. Copeia 1983, 1013-1023. https://doi.org/10.2307/1445104

Metz, T.L., Landry, A.M.J., 2013. An assessment of green turtle (Chelonia mydas) stocks along the Texas coast, with emphasis on the Lower Laguna Madre. Conserv. Biol. 12, 293–302.

Morton, R.A., McGowen, J.H., 1980. Modern Depositional Environments of the Texas Coast: Austin. Bur. Econ. Geol. Univ. Tex. Austin Guidebook 20, 167 p.

NOAA (National Oceanic and Atmospheric Administration) Climate.gov Media, 2022. Arctic Oscillation (AO), data from September 2004 – December 2019, https://www.climate.gov/media/13592

NOAA (National Oceanic and Atmospheric Administration) Earth System Research Laboratories (ESRL) Physical Science Laboratory, 2022. Pacific Decadal Oscillation (PDO), data from September 2004 – December 2019 (standard PSL format), https://psl.noaa.gov/gcos_wgsp/Timeseries/PDO/

NOAA (National Oceanic and Atmospheric Administration) Fisheries, 02/11/2021. Sea Turtle Stranding and Salvage Network Overview: U.S Gulf of Mexico statistical zone map, https://media.fisheries.noaa.gov/dam-migration/gulfofmexico_zone_map.png

NOAA (National Oceanic and Atmospheric Administration) National Centres for Environmental Information (a), 2022. El Niño/Southern Oscillation (ENSO): Southern Oscillation Index (SOI), data from September 2004 – December 2019, https://www.ncdc.noaa.gov/teleconnections/enso/soi

NOAA (National Oceanic and Atmospheric Administration) National Centres for Environmental Information (b), 2022. North Atlantic Oscillation (NAO), data from September 2004 – December 2019, https://www.ncdc.noaa.gov/teleconnections/nao/

NOAA (National Oceanic and Atmospheric Administration) Physical Science Laboratory, 2022. Climate Timeseries: AMO (Atlantic Multidecadal Oscillation) Index, data from September 2004 – December 2019 (AMO unsmoothed long: standard PSL format), https://psl.noaa.gov/data/timeseries/AMO/

NOAA (National Oceanic and Atmospheric Administration) Weather Prediction Center, 2022. Daily Weather Maps data from 28/11/2009 – 06/03/2010, 22/12/2012 – 05/02/2013, 01/11/2014 – 12/03/2015, and 26/11/2017 – 07/02/2018, https://www.wpc.ncep.noaa.gov/dailywxmap/index_20150117.html

QGIS.org, 2022. QGIS Geographic Information System. QGIS Association, http://www.qgis.org

Roberts, K., Collins, J., Paxton, C.H., Hardy, R., Downs, J., 2013. Weather patterns associated with green turtle hypothermic stunning events in St. Joseph Bay and Mosquito Lagoon, Florida. Grad. Theses Diss. Univ. South Fla.

Schwartz, F.J., 1978. and Tolerance Responses to Cold Water Temperatures by Three Species of Sea Turtles (Reptilla, cheloniidae) in North Carolina. Fla. Mar. Res. Publ. 33, 16–18.

Shamblin, B.M., Dutton, P.H., Shaver, D.J., Bagley, D.A., Putman, N.F., Mansfield, K.L., Ehrhart, L.M., Peña, L.J., Nairn, C.J., 2017. Mexican origins for the Texas green turtle foraging aggregation: A cautionary tale of incomplete baselines and poor marker resolution. J. Exp. Mar. Biol. Ecol. 488, 111–120. https://doi.org/10.1016/j.jembe.2016.11.009

Shaver, D.J., 1998. Sea turtle strandings along the Texas coast, 1980-94. In: Zimmerman R, editor. Characteristics and causes of Texas marine strandings. NOAA Tech. Rep. NMFS 143 Miami US Dep. Commer. 57–72.

Shaver, D.J., 2000. Distribution, residency, and seasonal movements of the green sea turtle, Chelonia mydas (Linnaeus 1758). Tex. PhD Diss. Tex. AM Univ.

Shaver, D.J., Hart, K.M., Fujisaki, I., Rubio, C., Sartain, A.R., 2013. Movement mysteries unveiled: spatial ecology of juvenile green sea turtles. In: Lutterschmidt WI, editor. Reptil. Res. Hauppauge Nova Sci. Publ. Inc 463–483.

Shaver, D.J., Tissot, P.E., Streich, M.M., Walker, J.S., Rubio, C., Amos, A.F., George, J.A., Pasawicz, M.R., 2017. Hypothermic stunning of green sea turtles in a western Gulf of Mexico foraging habitat. PLOS ONE 12, e0173920. https://doi.org/10.1371/journal.pone.0173920

Shideler, G.L., 1984. Suspended sediment responses in a wind-dominated estuary of the Texas Gulf Coast. J. Sediment. Petrol. 54, 731–745.

Simms, A.R., Anderson, J.B., Rodriguez, A.B., Taviani, M., 2008. Mechanisms controlling environmental change within an estuary: Corpus Christi Bay, Texas, USA, in: Special Paper 443: Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise. Geological Society of America, pp. 121–146. https://doi.org/10.1130/2008.2443(08)

Southeast Fisheries Science Center, 2022. Marine turtle stranding data – Sea Turtle Stranding and Salvage Network (STSSN) from 01/01/1998 – 31/12/2020. NOAA National Centers for Environmental Information, https://www.fisheries.noaa.gov/inport/item/27318

Still, B.M., Griffin, C.R., Prescott, R., 2005. Climatic and oceanographic factors affecting daily patterns of juvenile sea turtle cold-stunning in Cape Cod Bay, Massachusetts. Chelonian Conserv Biol 883–890.

Teas, W.G., 1993. Species composition and size class distribution of marine turtle strandings on the Gulf of Mexico and southeast United States coast, 1985–1991. NOAA Tech Memo NMFS-SEFSC-315 Miami US Dep. Commer.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94. https://doi.org/doi: 10.2307/210739

White, W.A., Calnan, T.R., Morton, R.A., Kimble, R.S., Littleton, T.G., McGowen, J.H., Nance, H.S., Schmedes, K.E., 1983. Submerged Lands of Texas, Corpus Christi Area: Sediments, Geochemistry, Benthic Macroinvertebrates, and Associated Wetlands: Austin, Texas. Bur. Econ. Geol. Univ. Tex. Austin 154 p.

Williams, N.C., Bjorndal, K.A., Lamont, M.M., Carthy, R.R., 2013. Winter diets of immature green turtles (Chelonia mydas) on a northern feeding ground: integrating stomach contents and stable isotope analyses. Estuaries Coast 37, 986–994.

Witherington, B.E., Ehrhart, L.M., 1989. Hypothermic Stunning and Mortality of Marine Turtles in the Indian River Lagoon System, Florida. Copeia 1989, 696. https://doi.org/10.2307/1445497

World Weather Online, 2022. Corpus Christi (78403) Historical Weather, data from 28/11/2009 – 06/03/2010, 22/12/2012 – 05/02/2013, 01/11/2014 – 12/03/2015, and 26/11/2017 – 07/02/2018, https://www.worldweatheronline.com/v2/historical-weather.aspx?q=78403

Yeager, K.M., Santschi, P.H., Schindler, K.J., Andres, M.J., 2006. The relative importance of terrestrial versus marine sediment sources to the Nueces–Corpus Christi estuary, Texas: An isotopic approach. Estuaries Coasts 29, 443–454.

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