Chelonian Conservation and Biology, 2005, 4(4):883–890

Climatic and Oceanographic Factors Affecting Daily Patterns of Juvenile Sea Turtle Cold-Stunning in Cape Cod Bay, Massachusetts

Brett M. Still[1], Curtice R. Griffin[1], and Robert Prescott[2]

[1]*Department of Natural Resources Conservation, University of Massachusetts, Amherst, Massachusetts 01003 USA [E-mail: brett_still@hotmail.com];*
[2]*Massachusetts Audubon Society, Wellfleet Bay Wildlife Sanctuary, P.O. Box 263, South Wellfleet, Massachusetts 02663 USA*

Abstract. – We examined the climatic factors that may affect the temporal patterns of juvenile sea turtle cold-stunning and whether local extent and temporal scale oceanographic and climatic factors that induce cold-stunning are different for different species. Using classification tree models, we demonstrate that juvenile Kemp's ridley *(Lepidochelys kempii)* and loggerhead *(Caretta caretta)* sea turtles cold-stun under slightly differing oceanographic and climatic conditions within any given year. In Cape Cod Bay, Massachusetts, cold-stunned juvenile Kemp's ridley sea turtles are recovered with greater frequency (55%) during November, while the vast majority of juvenile cold-stunned loggerhead sea turtles (79%) are recovered in December. Our classification tree models suggest cold-stunned juvenile Kemp's ridleys are more often recovered from 9 November to 9 December on days with sea surface temperatures between 7.0 and 10.4°C, wind speeds exceeding 5.3 m/s, air temperatures below 10.4°C, and barometric pressures exceeding 1009.5 mm. Our models also suggest cold-stunned juvenile loggerheads are recovered after 5 December on days with sea surface temperatures between 5.6 and 9.0°C, wind speeds exceeding 7.6 m/s, and barometric pressure exceeding 1015.9 mm. Mean straight carapace lengths (SCL) differed for the two species, Kemp's SCL = 26.9 cm ($n = 218$, range 18.4–37.2), and loggerheads SCL = 52.5 cm ($n = 54$, range 40.0–89.6). As a result, the larger sized loggerheads were able to withstand colder sea surface temperatures for longer periods of time due to greater thermoregulatory capabilities. These results demonstrate the seasonality of juvenile sea turtle cold-stunning in Cape Cod Bay, Massachusetts, providing oceanographic and climatic thresholds for the Sea Turtle Rescue and Salvage Network to maximize recovery efforts during peak cold-stunning conditions.

Key Words. – Reptilia; Testudines; Cheloniidae; *Lepidochelys kempii*; *Caretta caretta*; sea turtle; CART; classification tree modeling; cold-stunning; Cape Cod Bay; Massachusetts; USA

Portions of coastal New England waters are considered the northern-most developmental habitats for juvenile Kemp's ridley (*Lepidochelys kempii*) and loggerhead (*Caretta caretta*) sea turtles along the U.S. Atlantic coast (Bleakney, 1965; Lazell, 1976, 1980; Morreale et al., 1992; Shoop and Kenney, 1992; Morreale and Standora (In press). Morreale and Standora (In press) hypothesized that these food-rich developmental habitats are crucial for Kemp's ridley and loggerhead sea turtles as they shift from pelagic to early juvenile stages. In Long Island Sound, New York, Morreale and Standora (1994) reported measurable, and in some cases substantial, growth in carapace length for recaptured juvenile sea turtles over a three-month period from July through September. Yet, these northern developmental habitats can only be utilized for a relatively short period of time each year due to limited thermoregulatory capabilities of juvenile cheloniid sea turtles (Spotila et al., 1997).

During the fall, sea turtle species that utilize summer developmental habitats in northern temperate waters, such as New England, Long Island Sound, and Chesapeake Bay, migrate south along the coast with the onset of declining water temperatures (Henwood and Ogren, 1987; Keinath, 1993; Musick et al., 1994; Epperly et al., 1995). If these turtles do not migrate south early enough, they can be cold-stunned by rapidly dropping water temperatures in late fall and winter months.

Further, periodic cold fronts that produce rapidly dropping air temperatures and strong west to northwesterly winds are a common feature of the transition from summer to fall in New England. Along with the cold air temperatures and high winds, these storms trigger dropping sea surface temperatures, especially in shallow coastal embayments that are inhabited by juvenile sea turtles. These climatic and oceanographic conditions, in combination with the semi-enclosed embayment of Cape Cod, contribute to the annual occurrence of juvenile sea turtle cold-stunning events along the shores of Cape Cod Bay during November and December.

Previous studies of juvenile Kemp's ridley and loggerhead cold-stunning focused primarily on water temperature and prevailing wind direction as factors affecting the timing and recovery location of cold-stunned turtles. Schwartz (1978) reported juvenile turtles exhibit floating and lethargic behaviors at water temperatures between 9 and 13°C, with death occurring at temperatures ranging from 5.0 to 6.5°C. Witherington and Ehrhart (1989) and Burke et al. (1991) reported similar cold-stunning water temperature values, while also reporting that the prevailing wind direction was a dominant factor determining the recovery location of cold-stunned turtles.

While these studies do mention cold-front storms, or periods of unusually cold weather associated with cold-stunning events, few examined a variety of climatic and oceanographic factors. Thus, the objective of this study was to evaluate the local scale climatic and oceanographic factors that affect the date and location of juvenile sea turtle cold-stunning events in Cape Cod Bay, Massachusetts. We hope this information will facilitate more effective recovery efforts for cold-stunned sea turtles.

METHODS

Study Area. — Cape Cod Bay, the southern terminus of the Gulf of Maine, is a 1100 km^2 semi-enclosed embayment averaging 30 m in depth, with the deepest part located near the mouth of the bay off Provincetown (55 m). Bottom substrates vary throughout the bay; sand bottom predominates but rock and eelgrass (*Zostera marina*) also commonly occur. Many shallow tidal and inter-tidal sand flats, extending up to 2.4 km offshore in a very gentle slope, are found from Dennis on the mid-Cape extending eastward and northward to the Truro shoreline. There are two prominent rocky areas within the bay, one between Sesuit Harbor and Corporation Beach in Dennis, extending seaward approximately 3 km; a second more extensive area along the western shore from Manomet to Ellisville. Extensive eelgrass beds occur below mean low water off the Wellfleet and Truro shores. The most extensive eelgrass beds are found along Billingsgate Shoals and extend southwest of Wellfleet Harbor's entrance toward Sesuit Harbor in Dennis.

Cold-Stunned Turtle Data. — From the efforts of the Sea Turtle Stranding and Salvage Network (STSSN), data were available for cold-stunned turtles found on Cape Cod Bay beaches from 1979 through 2001. These data included information on species, date, location of stranding, and size (straight carapace length; SCL) for each cold-stunned turtle. Although all cold-stunned turtles were collected with the assistance of numerous volunteers, the protocols established by the STSSN help to ensure that all potential beaches are surveyed. Thus, we believe that the vast majority of turtles that cold-stunned in any given year were recovered.

For all analyses, any turtle records with missing data (species, date, or location) were omitted. For the classification tree analyses, we defined the cold-stunning season as 1 November – 31 December each year. Thus, any records of turtles recovered after 31 December were also omitted from these analyses. In addition, the turtle stranding data for 1979–83 were not included in the classification tree analyses because of uneven beach surveys and limited availability of sea surface temperature and climatic buoy data for those early years. Therefore, 914 turtles that stranded as a result of cold-stunning from 1984–2001, were included in our analyses.

To examine both the oceanographic and climatic conditions associated with cold-stunning events, we developed a binary response variable (0 = absent, 1 = present) to represent the daily occurrence of juvenile cold-stunned turtles washing ashore for both Kemp's ridley and loggerhead sea turtles, the two most common species to cold-stun in Cape Cod Bay. We performed these analyses for both species to determine if different cold-stunning conditions could be detected for the two species. Juvenile cold-stunned green (*Chelonia mydas*) sea turtles were not included in the models due to their relatively low recovery rate with only 30 (2.3%) recovered from 1979 to 2001.

Buoy Data. — We collected oceanographic and climatic data from the National Oceanographic and Atmospheric Administration (NOAA) buoy located 14 nautical miles east of Boston Harbor from November through December (1984–2001) (http://www.ndbc.noaa.gov). These data were used to represent conditions in Cape Cod Bay, due to the absence of any long term monitoring stations located within the bay. The hourly data recorded at the Boston buoy were averaged to obtain daily values for surface water temperature, air temperature, wind speed, and barometric pressure. We then averaged these daily values to represent the conditions over the three days prior to turtles washing ashore. This was done to lessen the effect on the data when turtles were recovered from beaches one or two days after the stranding conditions had passed. Hourly prevailing wind direction data were compiled to calculate a mean daily wind direction vector using Oriana software (Kovach, 1994). This mean daily vector was also averaged to represent the prevailing wind direction over the previous three days.

Model Statistics. — We used classification tree models to analyze the sea turtle cold-stunning and buoy data. These models are particularly useful as a data-mining tool for complex data with non-linear relationships, complex interactions, and missing values that are common in ecological data sets (De'ath and Fabricius, 2000). The main function of classification tree analysis is to explain the variation found in a single categorical response variable using either categorical or numeric explanatory variable(s) by developing a graphical binary recursive partitioning based 'tree' (Breiman et al., 1984; De'ath and Fabricius, 2000). The process begins with the undivided data in the 'root node', and subsequently partitioning the data into two homogeneous groups using simple binary splitting rule(s) based on the explanatory variable(s). Each split or 'branch' produces two 'nodes' that attempt to minimize the misclassification rate of the previous 'node'. Each of these 'nodes' is then split recursively until the maximum 'tree' is grown, where each 'terminal-node' or 'leaf' contains one case. The tree is then pruned back to an appropriate size to fit the data. Several splitting criteria and pruning methods were developed and explained by Breiman et al. (1984) and De'ath and Fabricius (2000).

For our classification tree analyses, the categorical response or dependent variable was the presence (1) or absence (0) of a cold-stunned Kemp's ridley or loggerhead each day of the cold-stunning season (1 November – 31 December) for each year from 1984 to 2001 ($n = 1098$ days).

A.

VARIABLE	DESCRIPTION
P3DWTMP	Avg. sea surface temp. recorded over the previous three-days
DAY	Julian date of the cold-stunning season
P3DATMP	Avg. air temp. recorded hourly over the previous three days
P3DBAR	Avg. barometric pressure recorded hourly over the previous three days
P3DWSPD	Avg. wind speed recorded hourly over the previous three days (m/s)
P3DPDIR	Avg. prevailing wind direction recorded over the previous three days

B.

VARIABLE	REL. IMP.
P3DWTMP	100
DAY	62.4
P3DATMP	24.6
P3DPDIR	1.6
P3DWSPD	0.8
P3DBAR	0.3

C.

VARIABLE	REL. IMP.
DAY	100
P3DATMP	27
P3DPDIR	0.7
P3DWSPD	0.5
P3DBAR	0.0

D.

VARIABLE	REL. IMP.
DAY	100
P3DATMP	30.8
P3DWSPD	18.3
P3DBAR	11.3
P3DPDIR	2.3

E.

VARIABLE	REL. IMP.
P3DWTMP	100
DAY	70
P3DATMP	56.9
P3DPDIR	12.7
P3DWSPD	2.0
P3DBAR	0.8

F.

VARIABLE	REL. IMP.
P3DWTMP	100
DAY	70
P3DATMP	61
P3DWSPD	30.1
P3DBAR	10.5
P3DPDIR	5.2

Table 1. Explanatory variables used in the Kemp's ridley and loggerhead presence/absence classification tree analyses **(A)**. Relative importance of the explanatory variables included in the Kemp's ridley and loggerhead presence/absence classification trees **(B, C, D, E, F)**.

We used 6 explanatory variables for each model, representing the oceanographic and climatic dynamics for each day of the cold-stunning season (Table 1A).

We built the classification tree models using program CART 4.0 (Salford Systems, 1998) with the following criteria. We ran a series of fifty 10-fold cross validations using Gini splitting criteria, with the appropriate tree size selected using the minimum rule (Breiman et al., 1984; De'ath and Fabricius, 2000). We plotted the cross-validation relative error versus the tree sizes produced for each of the 50 runs to develop a histogram of tree sizes where the modal tree size was selected as the most appropriate tree. We smoothed the cross-validation relative error curve by averaging the relative error for each cross-validation over the 50 runs (De'ath and Fabricius, 2000). We labeled the tree diagrams following the procedures of De'ath and Febricus (2000). Each split (non-terminal node) was labeled with the variable and its value that determined the split. Each 'leaf' or 'terminal node' was labeled with the 'terminal node' number (in parentheses), the dominant classification either present (1) or absent (0), the percentage of observations in the dominant class, and the number of observations, respectively.

RESULTS

Cold-Stunning. — In Cape Cod Bay, Massachusetts, a total of 1280 juvenile cold-stunned sea turtles (984 Kemp's, 266 loggerheads, and 30 greens) were recovered from 1979 to 2002 (annual mean = 53, range 6–277 turtles/yr). The majority of cold-stunnings occurred during November and December, with 85% recovered from 12 November to 17 December and relatively few dead turtles recovered from January to March the following year (Fig. 1). Juvenile cold-stunned loggerheads were generally recovered later in the cold-stunning season with 79% of all recoveries occurring in December, whereas the majority (55%) of cold-stunned Kemp's ridleys were recovered in November. The average SCL of Kemp's was smaller (mean = 26.9 cm, $n = 218$, range 18.4–37.2 cm) than that of loggerheads (mean = 52.5 cm, $n = 54$, range 40.0–89.6 cm).

The initiation of the November and December cold-stunning season is triggered by the decline of sea surface temperature (SST) in Cape Cod Bay, with juvenile Kemp's ridleys cold-stunning as the SST drops to approximately 10ºC (Fig. 2). The daily pattern of cold-stunning, however, is associated with the timing of cold-front storms passing through the region. During the 1999 cold-stunning season, for example, several strong cold-front storms generated dramatic increases in the number of cold-stunned turtles recovered per day (Fig. 2). These cold-front storms typically produce rapidly dropping air temperatures and increasing wind speeds, resulting in cold-stunned turtles washing ashore on windward facing beaches.

Prevailing Wind Direction. — The prevailing westerly wind direction associated with November and December cold-front storms is the most important factor in determining the beach recovery location of cold-stunned turtles. The overall daily mean prevailing wind direction during November and December from 1984 to 2002 was significantly oriented from a west to east direction, with a mean of 94.0º ($n = 1098$, range = 46–131º, circular s.d. = 70.5º, Rayleigh test of uniformity $p = 0.00$). These prevailing wind data correspond to the eastern shoreline of Cape Cod Bay where cold-stunned turtles are recovered each year, with 90% of all cold-stunned turtle recoveries occurring along the beaches of Truro to the north, and Dennis to the south (Fig. 3).

Classification Tree Models

Kemp's Ridleys. — The modal tree size for the daily Kemp's ridley presence absence model, selected by the minimum rule after a series of fifty 10-fold cross validations, contained 3-terminal nodes. This 3-terminal node classifica-

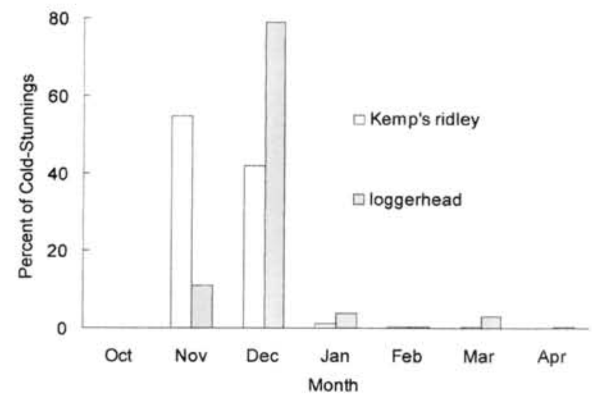

Figure 1. The highest percentages of juvenile sea turtle cold-stunnings in Cape Cod Bay are documented during November and December (1979–2002), with 55% of all Kemp's cold-stunning in November and 79% of all loggerhead stranding in December.

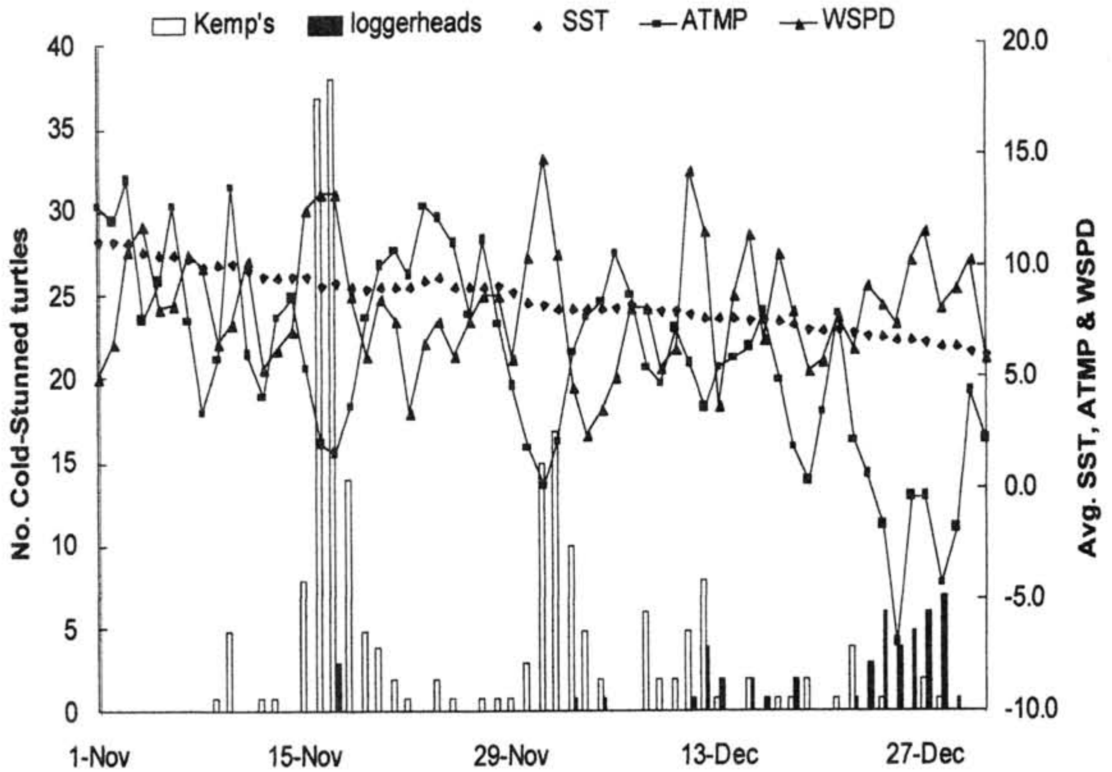

Figure 2. As the sea surface temperature (SST) in Cape Cod Bay drops below approx. 10°C, juvenile cold-stunned Kemp's ridleys begin cold-stunning and wash up on eastern Cape Cod Bay beaches, while juvenile loggerheads typically do not cold-stun until the SST drops to approx. 9.0°C. The daily pattern of juvenile sea turtle cold-stunning is driven by the occurrence of cold front storms. Large spikes in the number of cold-stunned turtles washing ashore occur with dramatic declines in air temperature (°C) (ATMP) and increasing wind speed (m/s) (WSPD). These daily patterns are clearly evident during the 1999 cold-stunning season.

tion tree had an overall misclassification rate of 35.6%, and misclassification rates of 13.9% and 43.3%, respectively for presence (1) and absence (0) (Fig. 4A). Of the 6 explanatory variables included in the model (Table 1A), the previous three-day sea surface temperature (P3DWTMP) was chosen as the primary splitting variable for the two splits in the tree. The presence (1) of cold-stunned Kemp's was predominant in the second terminal node, with the tree suggesting Kemp's were most likely to cold-stun at sea surface temperatures between 7.5 and 10.4°C (Fig. 5).

The relative importance of the explanatory variables included in the model indicated that sea surface temperature (P3DWTMP) was the most dominant (100) of the variables included, followed by the day of the cold-stunning season (DAY) (62.4) and average air temperature (P3DATMP) (24.6) having moderate importance (Table 1B). The prevailing wind direction (1.6), average wind speed (0.8) and average barometric pressure (0.3) had little relative importance in comparison to the previous three variables.

To examine the climatic factors without the influence of oceanographic temperature dynamics, we re-ran the analysis removing the dominant splitting variable (P3DWTMP). Using the same model building criteria as the previous tree, we obtained a modal tree size of 3-terminal nodes; however, strong support was also shown for an 8-terminal node tree being selected only 2% less than the modal tree size (Fig 4B). Both splits on the 3-terminal node tree used the date of the cold-stunning season (DAY) as the splitting variable, suggesting Kemp's are more likely to cold-stun between 9 November and 20 December (Fig. 6). Overall, the tree had a relatively high misclassification rate of 46.1%, with misclassification rates of 13.3 and 49.7%, respectively, for presence (1) and absence (0) of cold-stunned Kemp's (Fig. 6). The relative importance of the climatic variables used in the model after removing the dominant sea surface tempera-

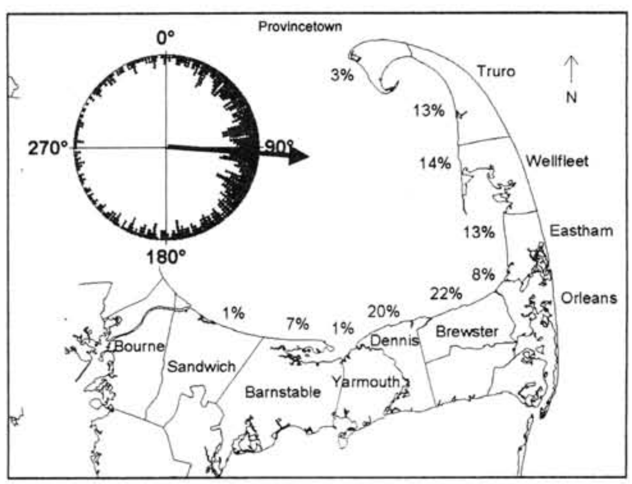

Figure 3. Juvenile cold-stunned sea turtles are primarily recovered along the eastern shoreline of Cape Cod Bay between Truro to the north, and Dennis to the south (percent recovered per area). These recovery locations correspond to the mean prevailing west to east wind direction recorded during the cold-stunning seasons from 1984–2001 (mean = 94.03°).

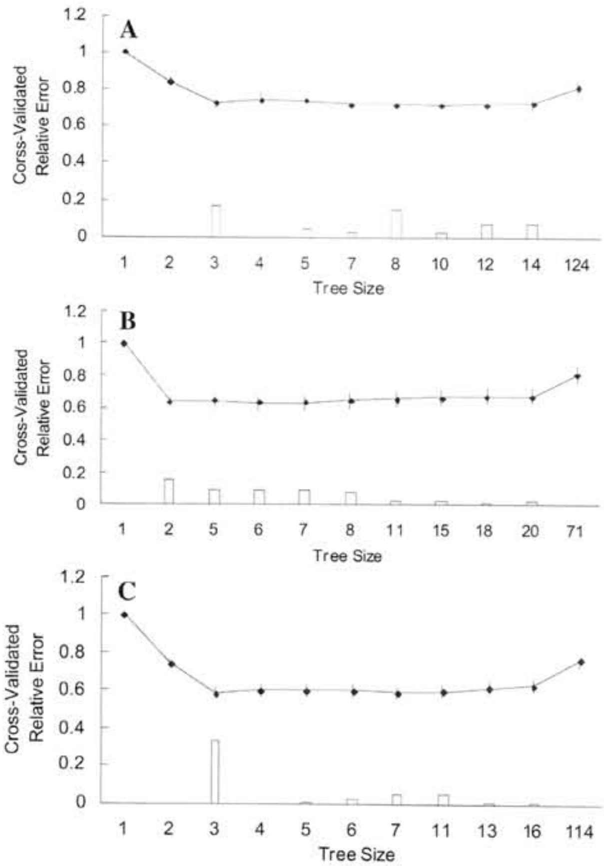

Figure 4. 10-fold cross-validated relative error curve averaged over 50 runs with 1 S.E. error bars for Kemp's ridley (**A** and **B**) and loggerhead (**C**) presence/absence models. The columns represent the relative frequency of tree sizes selected by the 50 runs.

ture variable (P3DWTMP) suggested the day of the cold-stunning season (DAY) has the greatest influence (100) followed by average air temperature (P3DATMP) with moderate support (27). The remaining three climatic variables had relatively little importance in the model (Table 1C).

The 8-terminal node tree (with P3DWTMP removed) used four splitting variables, predicting the presence of cold-stunned Kemp's in three of the eight terminal nodes (terminal nodes 3, 5, and 7). Further, this model yielded three slightly different cold-stunning scenarios (Fig. 7). All three cold-stunning scenarios began similar to the 3-terminal node tree that indicated that Kemp's cold-stunned between 9 November and 20 December. Additionally, scenario one (terminal node 3) suggested cold-stunned Kemp's were predominantly present before 9 December (DAY) when the average wind speed (P3DWSPD) was ≥ 5.3 m/s, and the average air temperature (P3DATMP) was ≤ 10.4°C (Fig. 7). The second cold-stunning scenario (terminal node 5) suggested that cold-stunned Kemp's were present under the same average wind speed and air temperature as scenario one, and after 9 December when the barometric pressure was > 1009.5 mm (Fig. 7). The final scenario (terminal node 7) showed Kemp's cold-stunning with the same wind speed (PEDWSPD) (≥ 5.3 m/s) as scenario one and two, and with cold-stunning after 24 November (DAY) when average air temperatures (P3DATMP) were ≥ 10.4°C (Fig. 7). The overall misclassification rate for this 8-terminal node tree was 38.2%, with misclassification rates of 11.5 and 47.6%, respectively, for presence (1) and absence (0) of cold-stunned Kemp's. The relative importance of the climatic variables used in the 8-terminal node classification tree was dominated (100) by the day of the cold-stunning season (DAY) followed by the average air temperature (P3DATMP) (30.8) and average wind speed (P3DWSPD) (18.3). The average barometric pressure (P3DBAR) showed moderate importance (11.3), with the average prevailing wind direction (P3DPDIR) showing little effect (2.3) on the model (Table 1D).

Loggerheads. — Our loggerhead presence/absence models also had strong support for a range of tree sizes. The modal tree size (2-terminal nodes) was selected by 22% of the fifty 10-fold cross-validations; however, three different tree sizes (5, 6, and 7-terminal nodes) exhibited the same prevalence, being selected 14% out of the 50 runs. Addition-

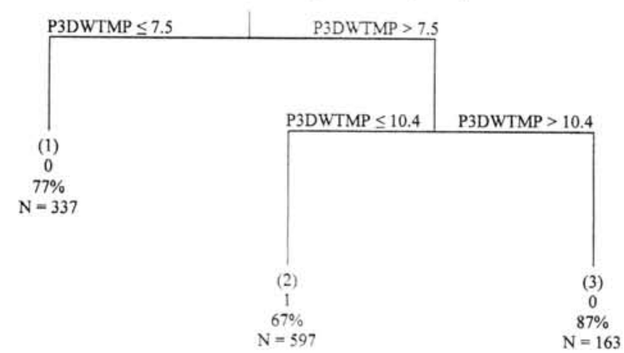

Figure 5. 3-terminal node classification tree model predicting the daily presence/absence of juvenile cold-stunned Kemp's ridley sea turtles in Cape Cod Bay during the cold-stunning season. Each terminal node is labeled with the node number (in parentheses), the dominant classification (1 = presence, 0 = absence), the percent dominance, and the number of cases in each terminal node, respectively. The two splits on the tree suggest Kemp's will cold-stun when Cape Cod Bay sea surface temperatures (P3DWTMP) are between 7 and 10.4°C. Overall misclassification = 35.6%, category 0 misclassification = 43.3%, category 1 misclassification = 13.9%.

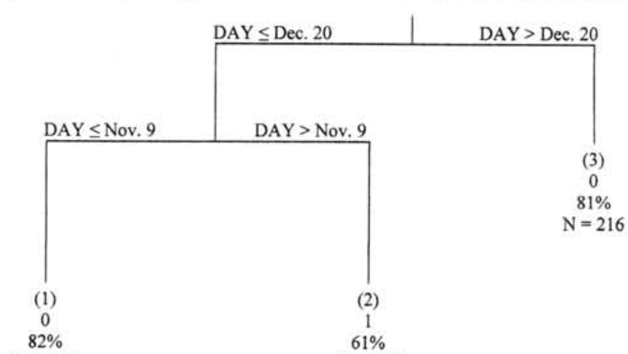

Figure 6. 3-terminal node classification tree model predicting the daily presence/absence of juvenile cold-stunned Kemp's ridley sea turtles in Cape Cod Bay during the cold-stunning season (P3DWTMP variable removed). The two splits on the tree suggest Kemp's will cold-stun on Cape Cod Bay beaches between 9 November and 20 December. Overall misclassification = 46.1%, category 0 misclassification = 59.1%, category 1 misclassification = 9.4%.

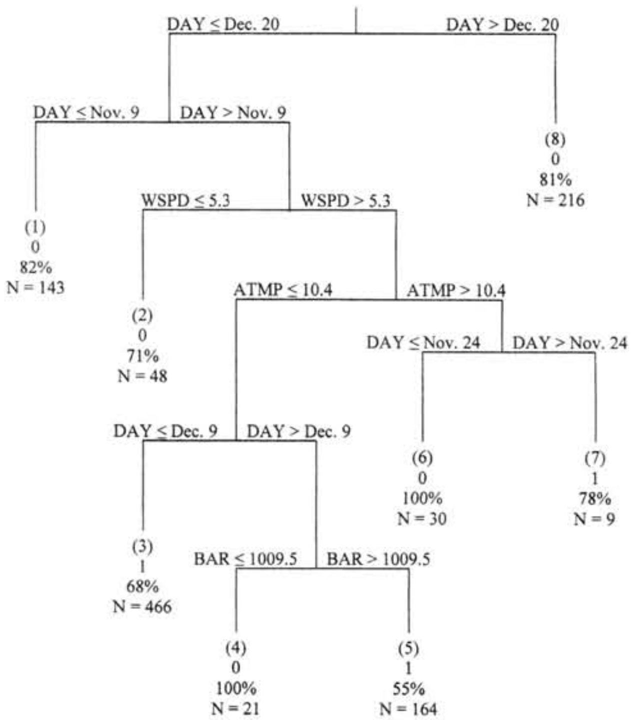

Figure 7. 8-terminal node classification tree predicting the daily presence/absence of juvenile cold-stunned Kemp's ridley sea turtles in Cape Cod Bay during the cold-stunning season (P3DWTMP variable removed). The model suggests Kemp's will be predominantly present in three of the eight terminal nodes (3, 5, and 7). Overall misclassification = 38.2%, category 0 misclassification = 47.6%, category 1 misclassification = 11.5%.

ally an 8-terminal node tree was selected only 2% less than the 5, 6, and 7-terminal node trees (Fig. 4C). We chose to describe the 7-terminal node tree in addition to the modal tree due to the strong support given to the larger tree size by the fifty 10-fold cross validations.

The 2-terminal node tree had an overall misclassification rate of 51.5%. However, the misclassification rate for detecting the presence of cold-stunned loggerheads (1) was much lower at 5.1%. This simple model split the data using average sea surface temperature (P3DWTMP), indicating loggerheads cold-stunned at water temperatures ≤ 9.0°C (Fig. 8). The average sea surface temperature (P3DWTMP) (100) followed by the day of the cold-stunning season (DAY) (70) and the average air temperature (P3DATMP) (56.9) had

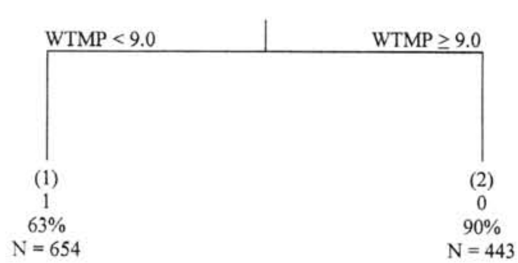

Figure 8. 2-terminal node classification tree suggesting cold-stunned loggerheads will be predominantly present (1) at sea surface temperatures below 9.0°C. Overall misclassification = 51.5%, category 0 misclassification = 56.1%, category 1 misclassification = 5.1%.

the highest relative importance of the six variables included in the model. Wind direction (P3DPDIR) (12.7) had moderate importance while wind speed (P3DWSPD) (2.0) and barometric pressure (P3DBAR) (0.8) had little influence in the model (Table 1E).

The 7-terminal node tree contained four of the six explanatory variables, with the average sea surface temperature (P3DWTMP) variable used repeatedly throughout the model. Loggerheads were predominantly present in two of the 7-terminal nodes (terminal nodes 4 and 6) (Fig. 9). As in the 2-terminal node model, the first split was based on the average sea surface temperature (P3DWTMP); indicating loggerheads do not cold-stun until average sea surface temperature falls below 9.0°C. The additional 5-terminal nodes explained a greater level of interaction between the climatic variables, suggesting two possible cold-stunning scenarios. Under the first scenario, loggerheads were likely to cold-stun after 5 December 5 (DAY = 188) when average sea surface temperatures (P3DWTMP) were between 7.1 and 9.0°C, average wind speed (P3DWSPD) ≤ 7.6 m/s, and average barometric pressure (P3DBAR) > 1015.9 mm (Fig. 9). The second scenario suggested loggerheads cold-stun when the average sea surface temperature (P3DWTMP) was between 5.6 and 9.0°C, and when the average wind speed (P3DWSPD) exceeded 7.6 m/s (Fig. 9).

The relative importance of the explanatory variables used in this classification tree was dominated by the average sea surface temperature (P3DWTMP) (100). Day of the cold-stunning season (DAY) (70), and average air tempera-

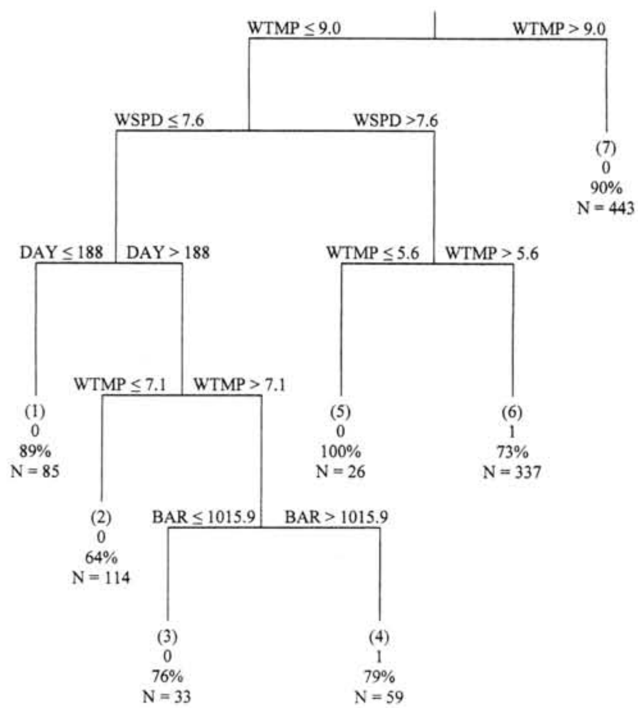

Figure 9. 7-terminal node classification tree predicting the daily presence/absence of juvenile cold-stunned loggerhead sea turtles in Cape Cod Bay during the cold-stunning season. The model suggests loggerheads will be predominantly present in two of the seven terminal nodes (4 and 6). Overall misclassification = 29.4%, category 0 misclassification = 31.1%, category 1 misclassification = 13.1%.

ture (P3DATMP) (61) also had relatively high importance values. Average wind speed (30.1) followed by average barometric pressure (10.5) and average prevailing wind direction (5.2) were moderately important in the model (Table 1F).

DISCUSSION

As in other studies (Witherington and Ehrhart, 1989; Burke et al., 1991), the prevailing wind direction associated with cold-front storms was the most important factor in determining the beach recovery location of cold-stunned turtles in Cape Cod Bay. Given the semi-enclosed orientation of Cape Cod, the prevailing wind direction determines the section of shoreline where cold-stunned turtles will most likely be recovered. In Long Island Sound, however, the prevailing wind direction also can determine the overall cold-stunning magnitude each year. Due to the east-west orientation of Long Island, turtles can be swept out of Long Island Sound, if the prevailing wind direction is oriented easterly (Burke et al., 1991).

The daily presence/absence cold-stunning models for Kemp's and loggerheads had similar overall structure and variable importance. However, for sea surface temperature and the day of the cold-stunning season, the values that determined the model splits varied. For example, sea surface temperature, when included, had the highest relative importance for both species models. Yet, the Kemp's models indicated they were more likely to cold-stun on days when the sea surface temperature was between 7.5 and 10.4°C, while for loggerheads the models suggested cold-stunning prevalence at sea surface temperatures between 7.1 and 9.0°C and 5.6 to 7.1°C, depending on the wind speed.

The timing of cold-stunning during the season, also important for both models, varied for both species, with the models suggesting Kemp's typically start cold-stunning much earlier in the season (ca. 9 November), followed later by loggerheads (ca. 5 December). This seasonality is most likely due to the dissimilar size of Kemp's and loggerheads that cold-stun each year in Cape Cod Bay: the mean SCL of Kemp's was smaller (26.9 cm) than that of loggerheads (52.5 cm). The larger size for loggerheads enhances their thermoregulatory capabilities and enables them to withstand colder sea surface temperatures for longer periods of time, relative to the much smaller Kemp's.

The misclassification rates for predicting the absence (0) of cold-stunned sea turtles were relatively high for both the Kemp's and loggerhead models. We believe this is due to years in the data when there were relatively few cold-stunned turtles recovered in Cape Cod Bay. We suspect that these years with low cold-stun turtle numbers represent years when there were few juvenile sea turtles in New England coastal waters (Still, 2003). Therefore, during years with few turtles in the region, no turtles would be recovered despite the occurrence of the oceanographic and climatic thresholds that trigger cold-stunning.

These classification tree results support the different cold-stunning patterns observed for Kemp's ridley and loggerhead sea turtles in Cape Cod Bay. Early in the season, Kemp's cold-stunning was most affected by the drop in sea surface temperatures. Once the sea surface temperatures fall below 10.4°C, and cold front storms pass through the region (low barometric pressures) with strong winds ranging from north to westerly directions, cold-stunned Kemp's begin to wash up onto windward facing beaches. Although node 5 suggested cold-stunned Kemp's would be present at barometric pressures exceeding 1009.5 mm, the mean barometric pressure during November and December from 1984 to 2001 was 1016.7 mm ($n = 1098$, range 994.0–1037.9).

Previous cold-stunning studies provided descriptions of the critical water temperature thresholds, but provided little description of the climatic factors associated with cold-front storms other than prevailing wind direction (Schwartz, 1978; Witherington and Ehrhart, 1989; Burke et al., 1991; Morreale et al., 1992; Moon et al., 1997). Schwartz (1978) reported that Kemp's, loggerheads, and greens exhibited cold-stunned floating behaviors in outdoor holding tanks at water temperatures between 9.0 and 13.0°C, with death occurring between 5.0 and 6.5°C for all species. In Long Island Sound, New York, Morreale et al. (1992) reported water temperatures below 10°C during the peak cold-stunning period of each year from 1985 to 1987. Moon et al. (1997) demonstrated that juvenile Kemp's ridley and green sea turtles, in controlled laboratory conditions, can adjust to slowly dropping water temperatures (5–6°C over an 8-week period), down to 15°C, without showing signs of severe cold stunning. Witherington and Ehrhart (1989) described a series of cold-stunning events in Mosquito Lagoon, Florida, from 1977 to 1986, where 342 greens, 123 loggerheads, and 2 Kemp's were recovered. These events were triggered by the arrival of severe cold fronts followed by several days of unusually cold weather. They reported early morning water temperatures generally below 8°C when turtles were recovered. They also suggested prevailing wind direction determined where the turtles would be found in the lagoon. Burke et al. (1991) also concluded prevailing wind direction was a dominant factor in determining the magnitude of cold-stunning events in Long Island Sound, New York, between 1985 and 1988.

Although this study enhances our understanding of the local extent and temporal scale factors that contribute to cold-stunning events in Cape Cod Bay, Massachusetts, it also provides a means to enhance recovery efforts of cold-stunned turtles by the Sea Turtle Stranding and Salvage Network. By monitoring sea surface temperature, the calendar date, wind speed and direction, and barometric pressure, the STSSN will be better able to maximize their recovery efforts during those days with the highest potential occurrence for cold-stunned turtles. This will help to mobilize the necessary staff, thereby increasing the survival rates of recovered turtles.

ACKNOWLEDGMENTS

We would like to thank the many UMASS faculty and graduate students in the Wildlife and Fisheries Conservation program for their help in exploring the fascinating world of statistics, including; Michel Sutherland, Kevin McGarigal, Sam Cushman, Maile Neel, Brad Compton, and Joanna Grand. Cheryl Ryder of the National Marine Fisheries Service and Tom French of the Massachusetts Division of Fisheries and Wildlife provided invaluable support and encouragement throughout the project. This work would not have been possible without the efforts of the countless volunteers and staff from the Massachusetts Audubon Society's Wellfleet Bay Wildlife Sanctuary, New England Aquarium Rescue and Rehabilitation Department, and members of the Cape Cod National Seashore involved in the Sea Turtle Stranding and Salvage Network. Their dedication and hard work have increased the survival chances of hundreds of cold-stunned turtles. Additionally, we are thankful for the financial support provided by the National Marine Fisheries Service and the NOAA CMER Program.

LITERATURE CITED

BLEAKNEY, J.S. 1965. Reports of marine life from New England and eastern Canada. Canadian Field-Naturalist 79:120-128.

BREIMAN, L., FRIEDMAN, J.H., OLSHEN, R.A., AND STONE, C.J. 1984. Classification and Regression Trees. Boca Raton: CRC Press, 368 pp.

BURKE, V.J., STANDORA, E.A., AND MORREALE, S.J. 1991. Factors affecting strandings of cold-stunned juvenile Kemp's ridley and loggerhead sea turtles in Long Island, New York. Copeia 1991(4):1136-1138.

CART. 1998. Salford Systems, San Diego, California.

DE'ATH, G. AND FABRICIUS, K.E. 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81(11):3178-3192.

EPPERLY, S.P., BRAUN, J., AND CHESTER, A.J. 1995. Aerial surveys for sea turtles in North Carolina inshore waters. Fishery Bulletin 93(2):254-261.

HENWOOD, T.A. AND OGREN, L.H. 1987. Distribution and migrations of immature Kemp's ridley turtles, *Lepidochelys kempi*, and green turtles, *Chelonia mydas*, off Florida, Georgia and South Carolina (USA). Northeast Gulf Science 9:153-159.

KEINATH, J.A. 1993. Movements and behavior of wild and head-started sea turtles. Ph.D. Thesis, College of William and Mary, Williamsburg, Virginia.

KOVACH, W.L. 1994. Oriana for Windows, version 1.06. Kovach Computing Services, Wales, U.K.

LAZELL, J.D., JR. 1976. This Broken Archipelago: Cape Cod and the Islands, Amphibians and Reptiles. New York: Demeter Press, 260 pp.

LAZELL, J.D., JR. 1980. New England waters: critical habitat for marine turtles. Copeia 1980(2):290-295.

MOON, D.Y., MACKENZIE, D.S., AND OWENS, D.W. 1997. Simulated hibernation of sea turtles in the laboratory: I. feeding, breathing frequency, blood pH, and blood gases. Journal of Experimental Zoology 278:372-380.

MORREALE, S.J. AND STANDORA, E.A. 1994. Occurrence, movement and behavior of the Kemps' ridley and other sea turtles in New York waters. Final Report to NYS Dept. of Env. Conservation, Return a Gift to Wildlife Program, April 1988 – March 1993.

MORREALE, S.J. AND STANDORA, E.A. 2005. Western North Atlantic waters: crucial developmental habitat for Kemp's ridley turtle and loggerhead sea turtles. Chelonian Conservation and Biology 4(4):872-882.

MORREALE, S.J., MEYLAN, A.B., SADOVE, S.S., AND STANDORA, E.A. 1992. Annual occurrence and winter mortality of marine turtles in New York waters. Journal of Herpetology 26(3):301-308.

MUSICK, J.A., BARNARD, D., AND KEINATH, J.A. 1994. Aerial estimates of seasonal distribution and abundance of sea turtles near the Cape Hatteras faunal barrier. In: Schroeder, B.A. and Witherington, B.E. (Compilers). Proceedings of the Thirteenth Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-341, pp. 121-123.

SCHWARTZ, F.J. 1978. Behavioral and tolerance responses to cold water temperatures by three species of sea turtles (Reptilia, Cheloniidae) in North Carolina. In: Henderson, G.E. (Ed.). Proceedings of the Florida and Interregional Conference on Sea Turtles. Florida Marine Research Publications 33:16-18.

SHOOP, C.R. AND KENNEY, R.D. 1992. Seasonal distributions and abundances of loggerhead and leatherback sea turtles in waters of northeastern United States. Herpetological Monographs 6:43-67.

SPOTILA, J.R., O'CONNOR, M.P., AND PALADINO, F.V. 1997. Thermal biology. In: Lutz, P.L. and Musick, J.A. (Eds.). The Biology of Sea Turtles. Boca Raton, FL: CRC Press, pp. 297-314.

STILL, B.M. 2003. Factors affecting juvenile sea turtle cold-stunning in Cape Cod Bay, Massachusetts. M.S. Thesis, University of Massachusetts, Amherst.

WITHERINGTON, B.E. AND EHRHART, L.M. 1989. Hypothermic stunning and mortality of marine turtles in the Indian River Lagoon System, Florida. Copeia 1989(3):696-703.

Received: 3 June 2003
Revised and Accepted: 18 December 2004