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WINTER MASS MORTALITY OF ANIMALS IN TEXAS BAYS

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ABSTRACT: The Texas coast experienced three unusually cold weather periods in the 1980's, one in 1983 and two in 1989, that caused massive fish kills. Identification of organisms killed and estimation of the number of estuarine fishes and invertebrates killed was accomplished through a systematic standardized approach utilizing airplanes, ground qualitative observations and quantitative counts, and trawling. Of 159 species identified, 103 were fishes, 45 were invertebrates, and 11 were vertebrates other than fishes. About 14 million fishes were killed in December 1983, 11 million in February 1989 and 6 million in December 1989; number of invertebrates killed ranged from 13,000 in February 1989 to 1,000,000 in 1983. These assessments are the largest in area and most comprehensive to be documented in the literature with known levels of precision. Methodology used provides reasonably precise estimates which managers can use to assess extensive widespread kills and subsequent impacts on affected populations. It is recommended that managers consider reducing fishing mortality on the remaining economically important populations after extensive kills to speed recovery of those populations.

Mortality of marine organisms due to events such as cold temperatures can have dramatic impacts on population abundance. Severe mortalities could lower recruitment from loss of spawners so recovery to pre-event levels is slow to occur. Information on mass mortalities are required by fishery managers to ensure that subsequent fishing mortality does not jeopardize long-term viability of populations. With knowledge of these natural mortalities, fisheries managers can enact measures to reduce fishing mortality which speeds recovery of the population.

Polar cold fronts have pushed into Texas and crossed the Gulf of Mexico to as far south as Nicaragua (Gunter and Hildebrand 1951). The near-shore Gulf of Mexico and adjacent waters are vulnerable to periodic mass mortalities of fishes due to cold temperatures because of limited openings between land masses separating shallow bays from the Gulf, especially when water temperature decreases rapidly (Bartlett 1856; Higgins and Lord 1927; Anonymous 1931; Storey and Gudger 1936; Storey 1937; Gunter 1941, 1945, 1952; Baughman 1947, 1951; Gunter and Hildebrand 1951; Simmons 1957, 1962; Moore 1976; Holt and Holt 1983). Impact of cold fronts on fish survival is lessened if the front is preceded by gradually decreasing water temperatures which allow poikilothermic animals to acclimate or move offshore (Gunter and Hildebrand 1951, Springer and Woodburn 1960, Dahlberg and Smith 1970). Cold also can affect size of fishes killed (Gunter 1947).

Methods used to estimate the magnitude of freeze mortalities were not well documented prior to 1983-84; precision of estimates was not determined. Generally, qualitative observations were made; few quantitative counts were made over a broad area. Estimations of kills were extrapolated to sections of the coast with little documentation of areal extent of a kill. As a result, reliable quantitative comparisons of the impacts of freezes are impossible. The Texas Parks and Wildlife Department (TPWD) implemented procedures in the 1970's to estimate numbers of fish killed during rotenone collections in Texas bays (Matlock et al. 1982). These procedures were sufficiently general for application, with some modification, to estimate the number of fish killed in mass mortality events. These procedures were applied to 3 mass mortalities that occured in the 1980's. This paper documents methods used to estimate mortality of fishes in a freeze in 1983 and two in 1989, and provides estimates of animals reported killed.

MATERIALS AND METHODS

A stepwise, standardized approach was used to estimate numbers of animals killed in catastrophic cold kills along the Texas coast (Fig. 1); over 100 persons participated in each survey. First, extensive reconnaissance of shoreline areas that were accessible by vehicle were made daily to 1) measure water temperatures; 2) determine when organisms began to die; and 3) record general observations for areal documentation of the kill so future ground counts could be made. Second, when dead organisms were observed, airplane flights were initiated to identify

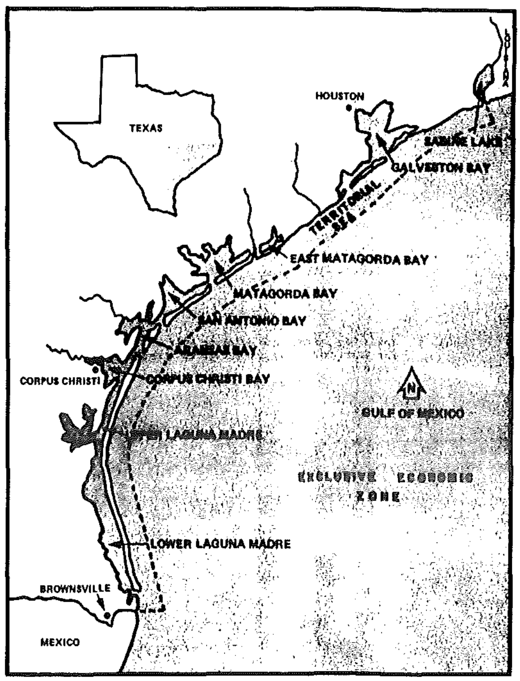

Figure 1. Texas bay systems.

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concentrations of dead organisms within each bay system. Third, based on these findings, bay systems were stratified into areas of high and low animal concentrations, which in turn were divided into shoreline and open water areas. In 1983, organisms were found to be distributed throughout the bay systems, so there was no stratification into high-low areas. Shoreline areas were accessed by boat or vehicle, and the number of dead animals in pre-selected random segments were counted. In the final phase, dead animals were collected on the bottom in open water areas using trawls after shoreline counting began.

In 1983, count (N = 242) or trawl (N = 100) sites were selected from existing shoreline and open water TPWD sample stations, whereas for 1989, shoreline counts (N = 118 February; 124 December) and trawl sites (N = 78 February; 107 December) were selected from a 1-minute latitude by 1-minute longitude grid system in each bay. Within each site or grid, three count areas, 30.5 m long, were randomly selected. To obtain the most precise estimates of numbers of dead fish, sampling was stratified (Cochran 1977) among bays and within each bay by observed high- and low-kill density areas. This procedure was used to select shoreline grids for sampling during 1989, whereas in 1983 simple random sampling was used to estimate numbers for each bay; in 1983 bays were treated as strata to estimate coastwide totals. At each shoreline area sampled, all dead fish and macro-invertebrates along shore, floating in the water or visible on bottom out to 15.2 m offshore were identified to species and counted; "other" animals were identified and recorded. Up to 19 randomly selected individuals of each species were measured (nearest 1 mm TL). Due to time constraints, if an estimated >500 animals were visually judged to be in a count area by the on-site counters, a randomly collected subsample was taken so a total area count estimate could be made.

The same site (in 1983) or grid (in 1989) system previously described was also used for trawls. Sites or grids were selected at random in identified kill areas. Trawls were pulled for 10 minutes in preselected grids without replication to estimate numbers of dead animals in water >1 m deep; one 10 minute pull with a 6.1-m trawl covered 0.35 ha. All dead animals were identified to species and counted; up to 19 individuals of each species in each 10 minute collection were measured.

Distribution of fish among sites (in 1983) or grids (in 1989) was highly skewed. Numbers at a few sites or grids were relatively high, whereas most sites or grids had few or no fish. The skewed distribution and large number of zeroes precluded using the raw data to compute unbiased estimators for the mean and standard error; log transformation failed to normalize the data. Therefore, Pennington's (1986) estimators, which are unbiased for skewed distributions with many zeroes, were used to compute mean and standard error of the number of organisms per site or grid for each stratum. All sites had roughly equal lengths and grids had approximately equal areas, so it was not necessary to standardize numbers collected for length or area sampled.

Total numbers and 95% confidence intervals of dead individuals of each species, and total number and 95% confidence interval for all species combined were computed for each bay and for the entire coast as follows (Scheaffer et al. 1979):

Total $= \Sigma N_i \bar{x}_i$

95% C. I. $= \text{Total} \pm 2 \sqrt{\Sigma N_i (N_i - n_i)\, s_i^2 / n_i}$

where $\bar{x}$ = mean number of dead fish per grid/site in stratum i

N_i = total number of grids/sites in stratum i

n_i = number of grids/sites sampled in stratum i

s_i^2 = variance of number of dead fish per grid/site in stratum i

Total number of dead individuals in open water areas based on trawl samples were estimated using the same procedures as described for shoreline estimates. For estimation purposes, the catch was assumed to be 100% of the dead animals available in the trawl path.

Separate mortality estimates (number) were developed for eight species of fishes and four species of invertebrates, all selected because of their economic importance. All species sampled were included in the total bay and coastwide estimates. Only length frequencies of selected fish are presented because invertebrates were not readily measurable even though identification to species was possible.

Estimates from shoreline counts and trawl collections were summed using standard statistical procedures to obtain total mortalities for each bay and the entire coast. Individual temperatures obtained from all ground observations, shoreline, and trawl grids/sites were pooled and averaged daily in a bay for presentation.

RESULTS

A total of 159 species (103 fishes, 45 invertebrates, 11 other vertebrates) had documented mortality during three freezes; species composition varied among freezes (Tables 1 and 2). We estimated about 14 million fishes and 1 million invertebrates were killed in 1983, 11 million fishes and 13,000 invertebrates in February 1989, and 6 million fishes and 155,000 invertebrates in December 1989 (Table 3). Striped mullet (*Mugil cephalus*), pinfish, (*Lagodon rhomboides*), Gulf menhaden (*Brevoortia patronus*), and bay anchovy (*Anchoa mitchilli*) collectively made up over 50% of the animals killed in each freeze. For fishes other than those estimated killed, the following constituted the majority of the estimate: bay anchovy with 41%, silver perch (*Bairdiella chrysoura*) with 39%, sand seatrout (*Cynoscion arenarius*) with 6%, and spot (*Leiostomus xanthurus*) with 3%. No consistent species percentage could be determined for "other invertebrates" killed; each species percentage varied widely among freezes.

Although fish mortalities resulting from freezing temperature occurred along the entire Texas coast, most deaths among species experiencing high mortalities generally occurred south of the San Antonio Bay system (Fig. 1, Table 2). However, over 90% of the Atlantic croaker (*Micropogonias undulatus*) killed in December 1989, and about 30% and 90% of the Gulf menhaden mortality in December 1983 and 1989, respectively, occurred in Galveston Bay. East Matagorda Bay accounted for about 70%, 50% and 50% of the black drum (*Pogonias cromis*), red drum (*Sciaenops ocellatus*), and spotted seatrout (*C. nebulosus*) killed, respectively during the February 1989 cold kill; this bay accounted for 60% of the striped mullet killed in December 1989. The Matagorda Bay system accounted for about 50% of the Gulf menhaden killed in December 1983. The San Antonio Bay system accounted for about 35% of the sheepshead (*Archosargus probatocephalus*) killed in February 1989.

A wide range of animals were killed in all freezes but the size classes affected apparently differed among freezes for each species; size composition provided an "instantaneous picture" of the effects on the population structure at the time of the kill. There were proportionally more small spotted seatrout (<300 mm TL) killed in the December freezes than in the February freeze (Fig. 2). Size composition

Table 1. List of common and scientific names of species killed during freezes of December 1983, February 1989, and December 1989.

Common name	Scientific name	Common name	Scientific name
Finfishes		Lined seahorse	*Hippocampus erectus*
Alligator gar	*Lepisosteus spatula*	Lined sole	*Achirus lineatus*
American eel	*Anguilla rostrata*	Longnose killifish	*Fundulus similis*
Atlantic bumper	*Chloroscombrus chrysurus*	Lookdown	*Selene vomer*
Atlantic croaker	*Micropogonias undulatus*	Molly miller	*Scartella cristata*
Atlantic cutlassfish	*Trichiurus lepturus*	Naked goby	*Gobiosoma bosci*
Atlantic midshipman	*Porichthys plectrodon*	Offshore tonguefish	*Symphurus civitatus*
Atlantic needlefish	*Strongylura marina*	Orange filefish	*Aluterus schoepfi*
Atlantic spadefish	*Chaetodipterus faber*	Permit	*Trachinotus falcatus*
Atlantic stingray	*Dasyatis sabina*	Pigfish	*Orthopristis chrysoptera*
Atlantic thread herring	*Opisthonema oglinum*	Pinfish	*Lagodon rhomboides*
Banded drum	*Larimus fasciatus*	Rainwater killifish	*Lucania parva*
Bar jack	*Caranx ruber*	Red drum	*Sciaenops ocellatus*
Bay anchovy	*Anchoa mitchilli*	Sailfin molly	*Poecilia latipinna*
Bay whiff	*Citharichthys spilopterus*	Sand seatrout	*Cynoscion arenarius*
Bearded brotula	*Brotula barbata*	Scaled sardine	*Harengula jaguana*
Bighead searobin	*Prionotus tribulus*	Scrawled cowfish	*Lactophrys quadricornis*
Blackcheek tonguefish	*Symphurus plagiusa*	Sharptail goby	*Gobionellus hastatus*
Black drum	*Pogonias cromis*	Sheepshead	*Archosargus probatocephalus*
Blackwing searobin	*Prionotus rubio*	Sheepshead minnow	*Cyprinodon variegatus*
Blue catfish	*Ictalurus furcatus*	Shoal flounder	*Syacium gunteri*
Chain pipefish	*Syngnathus louisianae*	Shrimp eel	*Ophichthus gomesi*
Channel catfish	*Ictalurus punctatus*	Silver perch	*Bairdiella chrysoura*
Clown goby	*Microgobius gulosus*	Skilletfish	*Gobiesox strumosus*
Code goby	*Gobiosoma robustum*	Smallmouth buffalo	*Ictiobus bubalus*
Common carp	*Cyprinus carpio*	Smallwing flyingfish	*Oxyporhamphus micropterus*
Cownose ray	*Rhinoptera bonasus*	Smoothhead scorpionfish	*Scorpaena calcarata*
Crested blenny	*Hypleurochilus geminatus*	Smooth puffer	*Lagocephalus laevigatus*
Crested cusk-eel	*Ophidion welshi*	Snapper eel	*Echiophis punctifer*
Crevalle jack	*Caranx hippos*	Snook	*Centropomus undecimalis*
Darter goby	*Gobionellus boleosoma*	Southern flounder	*Paralichthys lethostigma*
Diamond killifish	*Adinia xenica*	Southern kingfish	*Menticirrhus americanus*
Dwarf seahorse	*Hippocampus zosterae*	Southern stargazer	*Astroscopus y-graecum*
Fat sleeper	*Dormitator maculatus*	Southern stingray	*Dasyatis americana*
Finescale menhaden	*Brevoortia gunteri*	Speckled worm eel	*Myrophis punctatus*
Florida pompano	*Trachinotus carolinus*	Spot	*Leiostomus xanthurus*
Freckled stargazer	*Gnathagnus egregius*	Spotfin mojarra	*Eucinostomus argenteus*
Fringed flounder	*Etropus crossotus*	Spotted gar	*Lepisosteus oculatus*
Gizzard shad	*Dorosoma cepedianum*	Spotted seatrout	*Cynoscion nebulosus*
Gray snapper	*Lutjanus griseus*	Striped bass	*Morone saxatilis*
Gray triggerfish	*Balistes capriscus*	Stiped blenny	*Chasmodes bosquianus*
Green goby	*Microgobius thalassinus*	Stiped burrfish	*Chilomycterus schoepfi*
Green sunfish	*Lepomis cyanellus*	Stiped mullet	*Mugil cephalus*
Gulf butterfish	*Peprilus burti*	Threadfin shad	*Dorosoma petenense*
Gulf flounder	*Paralichthys albigutta*	Tidewater silverside	*Menidia peninsulae*
Gulf killifish	*Fundulus grandis*	Tripletail	*Lobotes surinamenis*
Gulf menhaden	*Brevoortia patronus*	White mullet	*Mugil curema*
Gulf pipefish	*Syngnathus scovelli*	Unidentified blenny	Blenniidae
Gulf toadfish	*Opsanus beta*	Unidentified drum	*Cynoscion* sp.
Hardhead catfish	*Arius felis*	Unidentified fish	Osteichthyes
Harvestfish	*Peprilus alepidotus*	Unidentified gar	*Lepisosteus* sp.
Hogchoker	*Trinectes maculatus*	Unidentified herring	Clupeidae
Inland silverside	*Menidia beryllina*	Unidentified Gerreidae	*Eucinostomus* sp.
Inshore lizardfish	*Synodus foetens*	Unidentified goby	*Gobiosoma* sp.
Ladyfish	*Elops saurus*	Unidentified jack	Carangidae
Lane snapper	*Lutjanus synagris*	Unidentified killifish	Cyprinodontidae
Least puffer	*Sphoeroides parvus*	Unidentified leatherjacket	Balistidae

Table 1. Continued.

Common name	Scientific name	Common name	Scientific name
Unidentified lefteye flounder	Bothidae	Pink shrimp	*Penaeus duorarum*
Unidentified mackerel	Scombridae	Pink purse crab	*Persephona crinita*
Unidentified mullet	*Mugil* sp.	Portly spider crab	*Libinia emarginata*
Unidentified pipefish	*Syngnathus* sp.	Red sea urchin	*Arbacia punctulata*
Unidentified seabass	Serranidae	Rough neck shrimp	*Trachypenaeus similis*
Unidentified searobin	*Prionotus* sp.	Sawtooth pen shell	*Atrina serrata*
Unidentified snake eel	Opichthidae	Sea walnut	*Beroe ovata*
Unidentified tonguefish	*Symphurus* sp.	Shark's eye	*Neverita duplicata*
		Sooty sea hare	*Aplysia brasiliana*
		Southern quahog	*Mercenaria campechiensis*
Invertebrates		Speckled swimming crab	*Arenaeus cribrarius*
Arrow shrimp	*Tozeuma carolinense*	Surf grassflat crab	*Dyspanopeus texana*
Atlantic mud crab	*Panopeus herbstii*	Surf mole crab	*Albunea gibbesii*
Atlantic brief squid	*Lolliguncula brevis*	Thin stripe hermit crab	*Clibanarius vittatus*
Atlantic surf clam	*Spisula solidissima*	White shrimp	*Penaeus setiferus*
Beach mole crab	*Albunea paratii*	Yellow box crab	*Calappa sulcata*
Big claw hermit crab	*Pagurus pollicaris*	Unidentified anemone	Actinaria
Big claw snapping shrimp	*Alpheus heterochaelis*	Unidentified clam	
Blue crab	*Callinectes sapidus*	Unidentified crab	Suborder reptantia
Brown shrimp	*Penaeus aztecus*	Unidentified mollusc	Phylum mollusca
Cabbagehead	*Stomalophus meleagris*	Unidentified mud crab	Xanthidae
Common Atlantic octopus	*Octopus vulgaris*	Unidentified penaeid shrimp	*Penaeus* sp.
Cryptic teardrop crab	*Pelia mutica*	Unidentified porcellanid crab	Porcellanidae
Dana swimming Gulf Crab	*Callinectes danae*	Unidentified portunid crab	Portunidae
Disk dosinia	*Dosinia discus*	Unidentified sea cucumber	Class Holothuroidae
Eastern oyster	*Crassostrea virginica*	Unidentified starfish	Asteroidea
Florida rock shell	*Thais haemastoma*	Unidentified trachypenaeid shrimp	*Trachypenaeus* sp.
Fragile Atlantic mactra	*Mactra fragilis*		
Grass shrimp	*Palaemonetes* sp.		
Green porcelain crab	*Petrolisthes armatus*	Other vertebrates	
Gulf grassflat crab	*Dyspanopeus texana*	American alligator	*Alligator mississippiensis*
Gulf stone crab	*Menippe adina*	Atlantic bottlenose dolphin	*Tursiops truncatus*
Harris mud crab	*Rhithropanopeus harrisii*	Kemp's ridley sea turtle	*Lepidochelys kempi*
Iridescent swimming crab	*Portunus gibbesii*	Brown pelican	*Pelecanus occidentalis*
Lesser blue crab	*Callinectes similis*	Double crested cormorant	*Phalacrocorax auritus*
Lightning whelk	*Busycon sinistrum*	Green turtle	*Chelonia mydas*
Long claw hermit crab	*Pagurus longicarpus*	Lesser scaup	*Aythya affinis*
Longnose spider crab	*Libinia dubia*	Unidentified reptile	Reptilia
Mantis shrimp	*Squilla empusa*	Unidentified seagull	Larinae
Minor jacknife clam	*Ensis minor*	Unidentified tern	Sterninae
Mottled purse crab	*Persephona mediterranea*	White pelican	*Pelecanus erythrorhynchus*

of red drum killed in December 1983 and February 1989 were similar, but red drum killed in December 1989 were generally larger (Fig. 2). Size composition of black drum killed in the two December freezes were similar, and generally larger than those killed in February 1989 (Fig. 3). The same pattern was evident for sheepshead and Atlantic croaker killed in February compared to those killed in December (Figs. 3 and 4), whereas Gulf menhaden killed in Decembers 1983 and 1989 were generally smaller than those killed in February (Fig. 4). Striped mullet killed in December 1983 included a greater proportion of small fish than in February or December 1989 (Fig. 5). Pinfish killed were about the same size in all three freezes (Fig. 5).

The pattern in daily water temperature fluctuations varied substantially among bays and among freeze events. Water temperatures dropped more rapidly and remained low longer during the December freezes than during the February freeze. Water temperatures

Table 2. Estimated number of fishes and invertebrates killed (No. X 1,000) during December 1983, February 1989 and December 1989 freezes by bay system. Number in parentheses = 96% confidence interval. ND = no data.

Species Date	Bay system: Sabine Lake	Galveston	Cedar Lakes	East Matagorda	Matagorda	San Antonio	Aransas	Corpus Christi	Upper Laguna Madre	Lower Laguna Madre	Coastwide
Finfish											
Atlantic croaker											
Dec-83	0[a]	53.3	0[a]	0.7[a]	1.0	0.3	39.6	46.8	9.3	37.2	188.3
		(0-121.7)		(0-1.8)	(0-2.1)	(0-0.6)	(3.2-76.2)	(0-107.7)	(1.3-17.3)	(0.1-84.7)	(57.8-315.9)
Feb-89	0	0	ND	0.1	0.5	0	0.2	0	22.6	10.1	33.4
				(0-0.3)	(0-6.2)		(0-1.0)		(0-66.3)	(0-26.2)	(3.1-65.2)
Dec-89	1.0	49.8	ND	<0.1	0	0	0.3	0.6	1.9	0.2	53.8
	(0.1-1.9)	(0-162.4)		(0-0.1)			(0-2.2)	(0-2.7)	(0-11.0)	(0-0.5)	(1.7-154.5)
Black drum											
Dec-83	0.1[a]	16.4	0.1[a]	3.3[a]	3.4	5.6	13.9	49.5	126.6	55.1	274.2
	(0-0.3)	(0-51.1)	(0-0.4)	(<.1-6.7)	(0.6-6.2)	(1.8-9.4)	(3.3-28.0	(2.2-96.8)	(0-257.3)	(14.1-107.2)	(91.0-455.0)
Feb-89	0	0	ND	89.9	0	9.3	29.7	0	2.7	1.6	133.1
				(15.8-164.0)		(0-104.4)	(10.2-49.2)		(0-20.8)	(0-3.5)	(60.8-204.4)
Dec-89	6.5	0.1	ND	5.6	0	7.5	112.5	9.2	330.4	16.0	487.8
	(0.8-12.1)	(0-2.0)		(1.9-9.4)		(0-23.8)	(0-589.6)	(0-31.2)	(0-1,203.8	(1.8-65.3)	(59.3-919.3)
Gulf menhaden											
Dec-83	0[a]	290.6	0.1[a]	7.1[a]	452.4	48.4	112.0	50.0	26.1	0.3	986.9
		(62.8-518.6)	(0-0.4)	(0-15.8)	(0-1,346.2)	(0-125.5)	(16.3-262.9)	(0-107.7)	(0-85.9)	(0-0.8)	(256.1-2,286.1)
Feb-89	0	0	ND	0.1	0	0	446.4	0	0	<0.1	446.4
				(0-0.3)			(0-1,362.2)			(0-0.1)	(0-1,213.9)
Dec-89	5.8	146.0	ND	2.4	0	0	<0.1	0.1	0	6.7	161.1
	(0-14.6)	(0-367.9)		(0-6.7)			(0-0.4)	(0-0.4)		(0-66.2)	(0-355.8)
Pinfish											
Dec-83	0[a]	1.5	0[a]	0.3[a]	11.1	0.3	111.5	2,977.2	91.4	99.9	3,292.9
		(0-4.2)		(0-0.6)	(0-34.8)	(0-0.6)	(0-306.1)	(13.6-6,749.9)	(0-222.8)	(0-222.7)	(13.4-6,956.2)
Feb-89	0	0	ND	0.2	0	7.0	85.0	0	144.9	28.0	265.0
				(0-0.5)		(0-21.3)	(0-180.7)		(0-1,376.2)	(0-63.0)	(6.7-534.6)
Dec-89	0	0	ND	0.1	0	0	7.7	305.8	0	38.4	352.0
				(0-0.3)			(0-54.8)	(0-1,553.4)		(0-514.4)	(0-990.0)
Red drum											
Dec-83	0[a]	0.3	0.1[a]	0.5[a]	12.1	25.9	27.3	0.3	5.1	32.2	103.8
		(0-0.7)	(-0.4)	(0-1.1)	(0-36.6)	(4.2-59.4)	(1.6-56.5)	(0-0.8)	(0-10.6)	(4.0-84.8)	(36.1-168.0)
Feb-89	0	0	ND	23.5	0.4	1.5	26.8	0	0.5	0.2	53.0
				(3.1-44.2)	(0-5.0)	(0-4.8)	(7.3-46.3)		(0-4.1)	(0-0.5)	(33.5-72.6)
Dec-89	0.7	15.1	ND	0.4	0	7.8	23.3	0.1	15.4	3.5	66.4
	(0.4-1.0)	(0-50.7)		(0.2-0.7)		(0.3-24.4)	(0-61.3)	(0-0.5)	(0-42.5)	(0.6-13.1)	(23.1-115.1)
Sheepshead											
Dec-83	0.2[a]	8.1	0.1[a]	4.3[a]	14.5	17.3	26.3	44.9	37.8	74.4	227.9
	(0-0.5)	(1.0-15.3)	(0-0.2)	(0.3-8.4)	(3.2-25.7)	(4.6-30.0)	(5.8-50.4)	(4.1-92.0)	(16.1-59.5)	(10.5-149.4)	(131.7-323.2)
Feb-89	0	0	ND	11.6	0.6	28.6	38.5	0	2.2	1.4	83.0
				(0-26.9)	(0-7.5)	(0-63.7)	(14.2-62.7)		(0.7-3.7)	(0-2.9)	(33.3-135.9)
Dec-89	13.0	0	ND	0.2	0.1	7.5	4.5	0.4	15.8	4.8	46.4
	(2.8-23.3)			(0-0.6)	(0-0.3)	(0-23.8)	(0-15.9)	(0-1.4)	(0-38.2)	(0-29.7)	(23.0-74.9)
Spotted seatrout											
Dec-83	0.2[a]	64.5	0.1[a]	0.9[a]	1.4	15.4	246.6	124.1	43.1	127.6	623.9
	(0-0.5)	(0-168.8)	(0-0.2)	(0.2-1.6)	(0.1-2.7)	(0.5-42.0)	(61.7-431.5)	(26.1-222.2)	(0-101.2)	(4.1-301.2)	(330.3.6-922.6)
Feb-89	0	0	ND	170.4	0.2	21.2	76.1	0	48.6	34.3	350.7
				(0-352.6)	(0-2.1)	(0-53.4)	(15.1-137.0)		(0-173.7)	(0.8-72.5)	(197.5-503.8)
Dec-89	13.6	94.8	ND	0.6	8.7	7.7	135.9	23.7	103.9	20.2	409.1
	(0-27.9)	(17.0-180.7)		(0.3-0.9)	(0-25.1)	(0-24.2)	(0-559.7)	(0-87.0)	0-380.7)	(0-219.9)	(183.4-634-7)

Table 2. Continued.

Striped mullet											
Dec-83	0.8ª	295.6	16.1ª	178.4ª	566.7	192.1	301.7	120.2	512.0	3,245.6	5,428.9
	(0.2.4)	(79.3-511.8)	(0-41.3)	(26.1-330.7)	(8.8-1,133.1)	(31.3-374.5)	(119.6-483.9)	(37.7-218.4)	(122.7-901.2)	(0-6, 712.2)	(2,355.8-8,484.9)
Feb-89	0	22.4	ND	21.2	0.2	3.4	64.7	2.1	7.0	53.9	174.8
		(0-68.4)		(0-46.2)	(0-2.9)	(0-9.9)	(17.2-118.2)	(0-26.7)	(0-38.5)	(0-162.3)	(59.8-319.9)
Dec-89	5.1	44.8	ND	2,664.1	45.7	26.7	137.2	14.4	270.6	828.5	4,057.3
	(0-11.3)	(0-146.2)		(1,585.1-3,784.6)	(0-103.0)	(0-61.5)	(0-420.6)	(0-49.3)	(0-625.5)	(0-1,990.7)	2,466.9-5,647.6)
Total fishes											
Dec.-83	1.2ª	1,253.7	25.4ª	214.9ª	713.3	341.9	1,800.4	4,250.8	985.9	4,805.3	14,392.7
	(0-3.0)	(473.6-2,033.8)	0-65.5)	(45.4-384.4)	(101.9-1,324.6)	(62.1-663.6)	(703.0-2,879.8)	(282.2-8,229.8)	(300.7-1,697.6)	(234.1-9,867.7)	(8,518.5-20,405.2)
Feb-89	0	22.4	ND	384.6	2.1	143.6	1,261.1	2.1	9,344.4	155.4	11.315.6
		(0-68.4)		(<1-984.9)	(0-27.9)	(0-324.2)	(386.3-2,140.8)	(0-26.9)	(0-116,619.9)	(14.8-321.9)	(20.8-28,597.0)
Dec-89	60.9	861.0	ND	2,699.8	83.0	61.7	436.0	451.1	703.7	813.7	6,170.9
	(11.4-110.3)	(0-1,798.4)		(1,592.4-3,806.3)	(0-176.8)	(0-133.0)	(111.7-767.7)	(0-1,973.8)	(0-1,698.8)	(0-2,670.7)	(3,798.8-8,543.1)
Invertebrates											
Blue crab											
Dec-83	6.9ª	1.3	1.4ª	5.9ª	8.7	8.2	44.9	1.6	0.9	68.3	148.2
	(0-19.7)	(0-2.9)	(0-4.5)	(0-14.2)	(0-20.1)	(2.4-14.1)	(0-90.6)	(0.1-3.1)	(0.2-1.6)	(1.6-136.1)	(62.0-234-6)
Feb-89	0	0	ND	0	0	0	0	0	0	4.1	4.1
										(0-9.7)	(0-9.7)
Dec-89	0	31.2	ND	<.1	0	0	0.1	0	0	0.1	31.4
		(0-79.4)		(0-0.1)			(0-0.7)			(0-0.2)	(<.1-74.9)
Brown shrimp											
Dec-83	0ª	15.9	0ª	0ª	11.0	0.7	17.7	0	0	78.4	123.7
		(0-49.7)			(0-34.3)	(0-2.3)	(0-35.6)			(0-196.8)	(23.3-224.4)
Feb-89	0	0	ND	0	0	7.0	0	0	0	0	7.0
						(0-21.3)					(0-20.2)
Dec-89	0	0	ND	0	0	0	0.1	0	0	0	0.1
							(0-1.6)				(0-0.3)
Pink shrimp											
Dec-83	0ª	0	0ª	0ª	0	0	67.2	0	0	0	67.2
							(13.7-120.8)				(15.9-118.5)
Feb-89	0	0	ND	0	0	0	1.7	0	0	0	1.7
							(0-5.8)				(0-5.1)
Dec-89	0	0	ND	0	0	0	0.1	0.1	0	0	0.1
							(0-1.1)	(0-0.4)			(0-0.4)
White shrimp											
Dec-83	0ª	173.6	0ª	0.2ª	11.5	21.5	60.0	0	0	51.0	317.8
		(47.4-299.7)	ND	(0-0.7)	(0-35.9)	(0-58.6)	(23.4-96.6)			(0-118.1)	(164.1-474.4)
Feb-89	0	0	ND	0	0	0	0	0	0	0	0
Dec-89	0	31.2	ND	0	0	0	0	24.5	0	0	55.7
		(0-79.4)						(0-80.0)			(0-120.2)
Total invertebrates											
Dec-83	6.9ª	551.0	1.4ª	6.6ª	12.6	33.7	212.2	117.2	17.5	357.5	1,316.5
	(0-19.7)	(0-1,193.7)	(0-4.5)	(0-15.8)	(0-28.0)	(2.9-75.1)	(72.4-352.8)	(0-333.4)	(0-41.3)	(112.8-602.1)	(291.6-2,288.2)
Feb-89	0	0	ND	0.2	0	7.0	1.8	0	0	4.4	13.4
				(0-0.5)		(0-21.3)	(0-5.8)			(0-11.2)	(0-31.3)
Dec-89	0	100.5	ND	<.1	<.1	17.6	7.0	25.7	0.1	4.0	155.1
		(0-216.5)		(0-0.1)	(0-0.5)	(0-44.6)	(0-24.3)	(0-83.4)	(0-0.4)	(0-25.6)	(36.3-273.9)

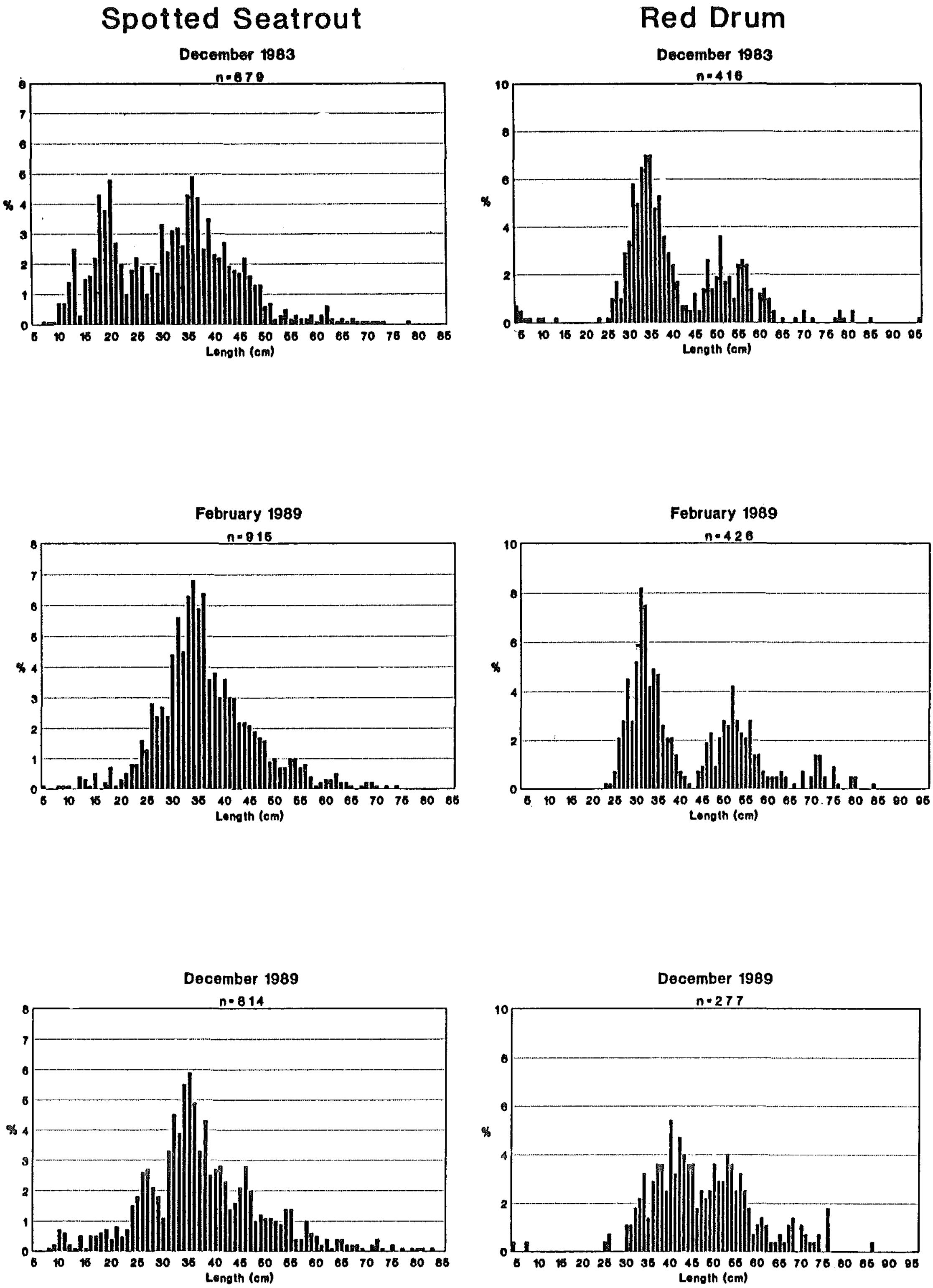

Figure 2. Length frequencies (midpoint of 10 mm groups) of spotted seatrout (*Cynoscion nebulosus*) and red drum (*Sciaenops ocellatus*) killed in three freezes.

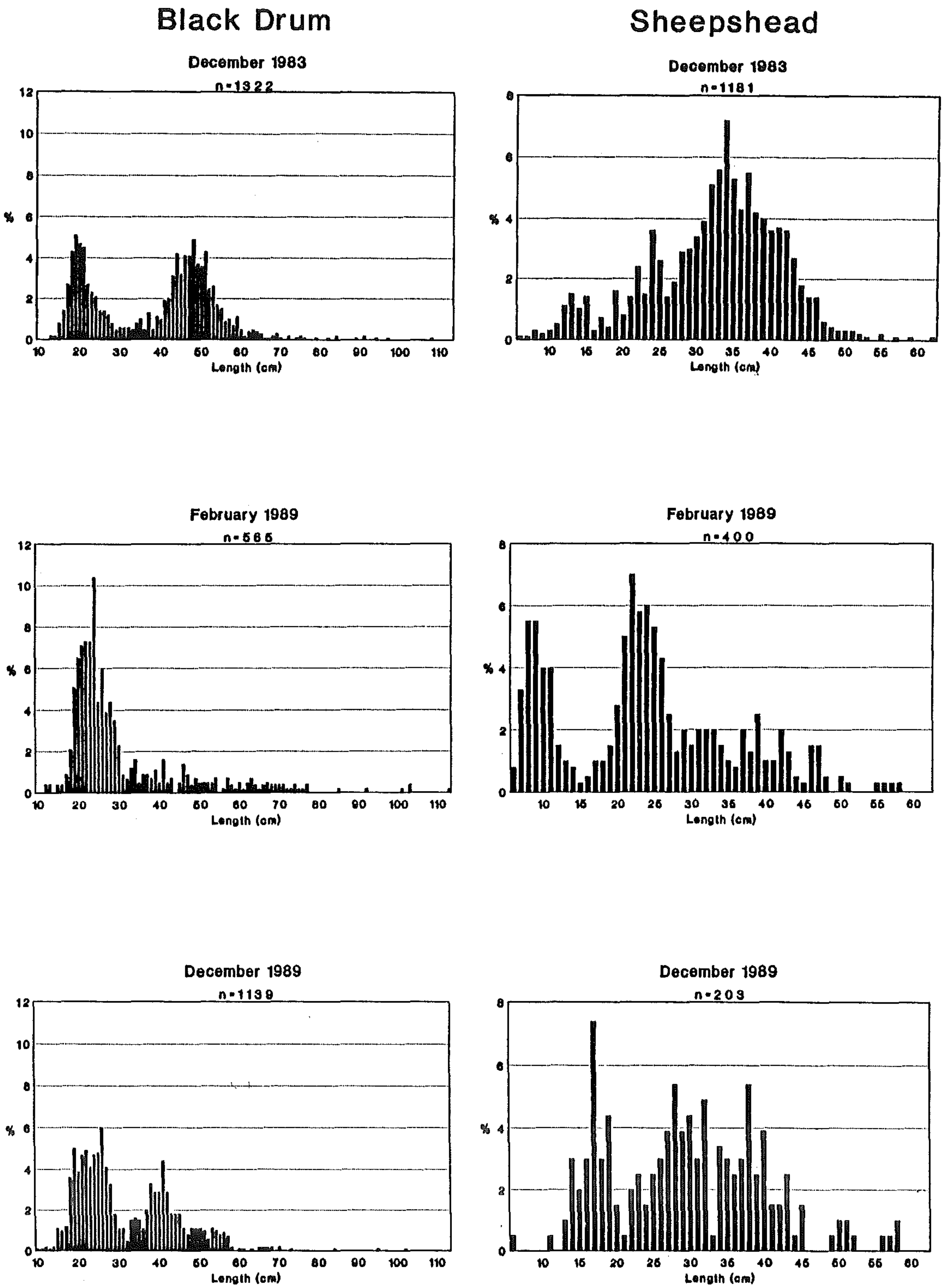

Figure 3. Length frequencies (midpoint of 10 mm groups) of black drum (*Pogonias cromis*) and sheepshead (*Archosargus probatocephalus*) killed in three freezes.

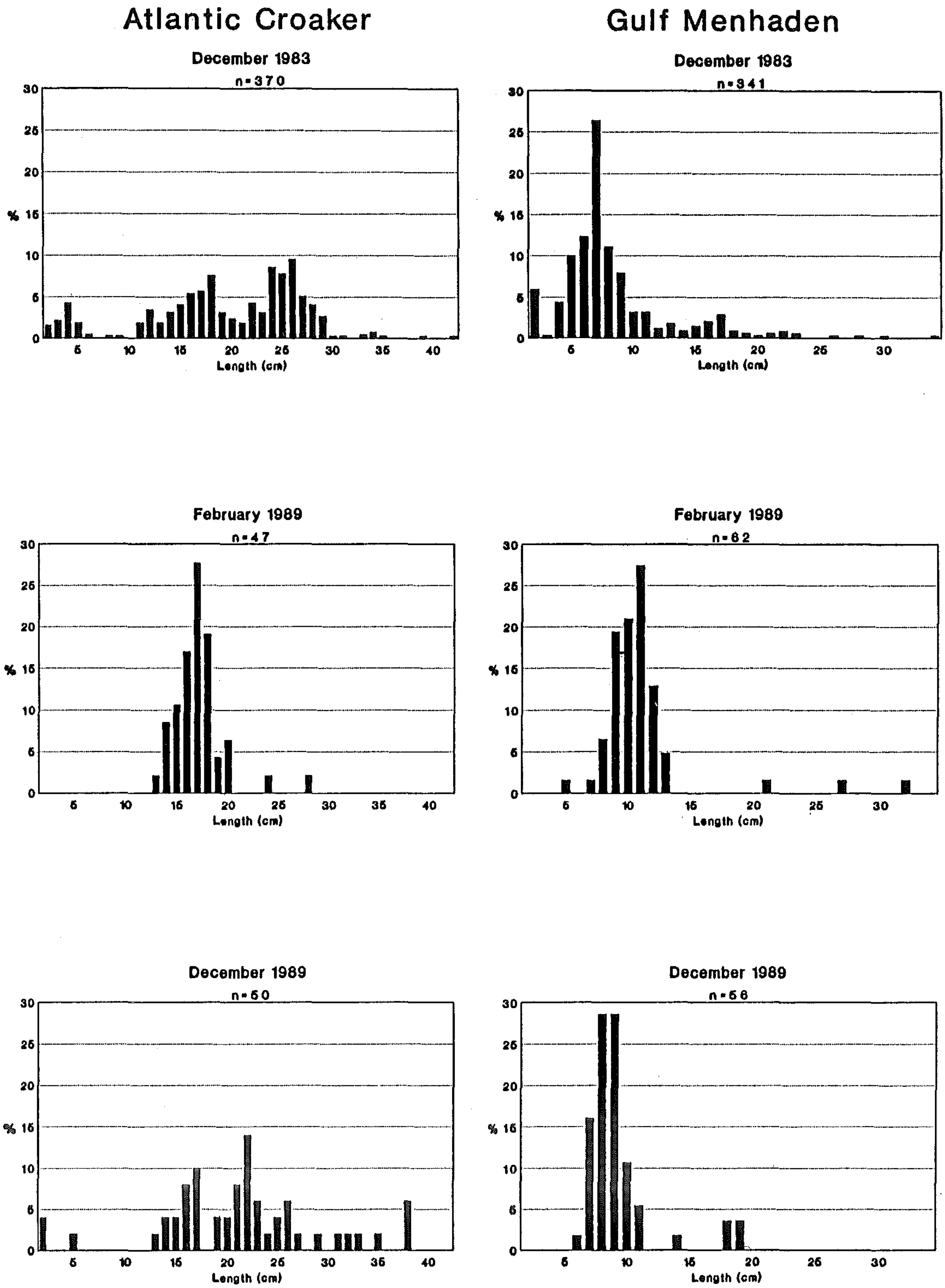

Figure 4. Length frequencies (midpoint of 10 mm groups) of Atlantic croaker (*Micropogonias undulatus*) and Gulf menhaden (*Brevoortia patronus*) killed in three freezes.

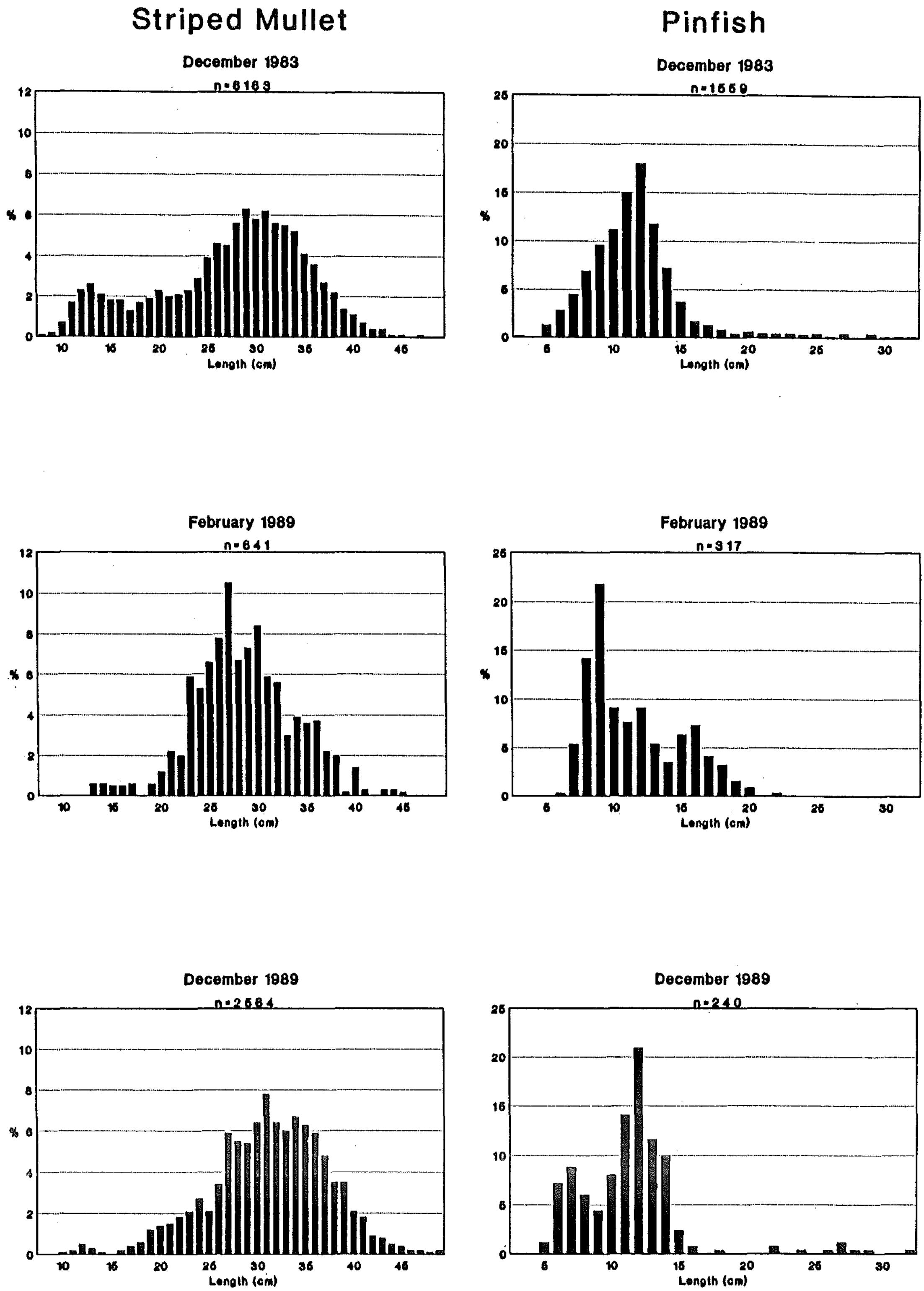

Figure 5. Length frequencies (midpoint of 10 mm groups) of striped mullet (*Mugil cephalus*) and pinfish (*Lagodon rhomboides*) killed in three freezes.

remained low longer during the December 1983 freeze than during the December 1989 freeze. Temperatures were about 10°C in each bay on 20 December 1983 (Fig. 6). By 26 December the temperature had decreased steadily to near 0° C in each bay. Temperatures remained between 0 and 5° C until about 1 January 1984 after which they increased steadily. Temperatures in February 1989 generally decreased from about 15 to 20° C on 2 February 1989 to between 0 and 10° C by about 8 February, depending on the bay system (Fig. 7). In each bay, temperatures began a general increase within about 2 days after reaching their low levels. The most rapid temperature declines and coldest temperatures occurred in both upper and lower Laguna Madre; warmest temperature occurred in Aransas and Corpus Christi Bays. During December 1989 temperatures decreased from about 10 to 15° C on 10 December to near 0° C by about 23 December after which they began to increase (Fig. 8).

DISCUSSION

Based on a search of the literature, fish kill assessments presented in this paper are the greatest in area and most comprehensive to be conducted with estimated levels of precision. The systematic, four-phase approach documented in this paper can be applied to any widespread and extensive kill as the result of major pollution events, red tide (*Gymnodinium breve*) blooms (Trebatoski 1988) or algae blooms.

Sampling procedures used during these three freezes produced useable estimates of the magnitude of fishes and invertebrates killed. However, mortality was underestimated, especially for small animals (<200 mm) because scavenging by birds and other animals undoubtedly occurred. Although illegal, fishermen also removed an unknown number of dead or dying fish during the freezes by foul hooking, dip netting, or picking up fish along the shoreline. These activities caused us to underestimate fish killed because fish were removed prior to our census.

Even though the estimates are biased low, they provide a relative measure of the immediate impact of freezes on marine populations. These estimates, in conjunction with fishery independent sampling data (Kana et al. 1993) from before and after the freezes can provide insights into the impact on populations affected. Because of the magnitude of marine fishing effort and economic value of recreational and commercial fisheries, it would behoove managers to assist populations to recover quicker than would naturally occur under unabated intense fishing pressure. To enhance recovery to pre-freeze levels for economically important fish populations, managers can respond by reducing subsequent fishing mortality through imposition of reduced bag and possession limits, increased size limits, gear restrictions, and closed areas (Anonymous 1985) immediately following a large-scale kill of fishes. The strategy is to reduce fishing mortality on spawning adult fish to allow many of them to spawn. In theory, if recruitment were density-dependent, compensatory mechanisms would allow many recruits to survive to maturity and spawn, thus increasing the size of the fishable population. The ability to detect reductions in fish populations suffering mass mortalities may be difficult if the index of abundance has a large coefficient of variation (Vaughn et al. 1986). Nonetheless, it seems prudent for managers to consider implementing regulations reducing subsequent fishing effort immediately following a large-scale kill.

Impact of cold weather on marine organisms in Texas bays varies sub-

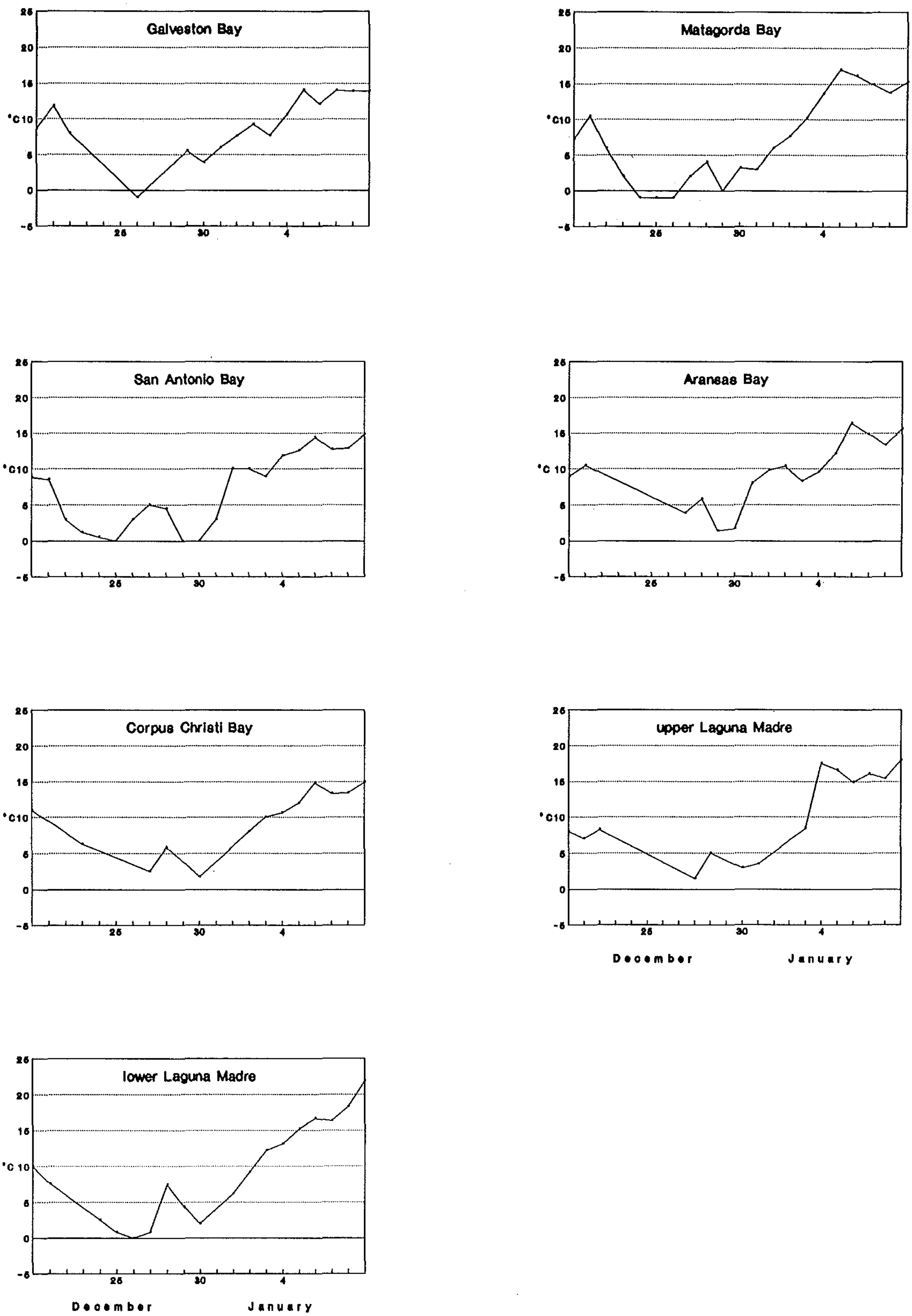

Figure 6. Daily mean water temperatures (°C) in Texas bays during December 1983 and January 1984.

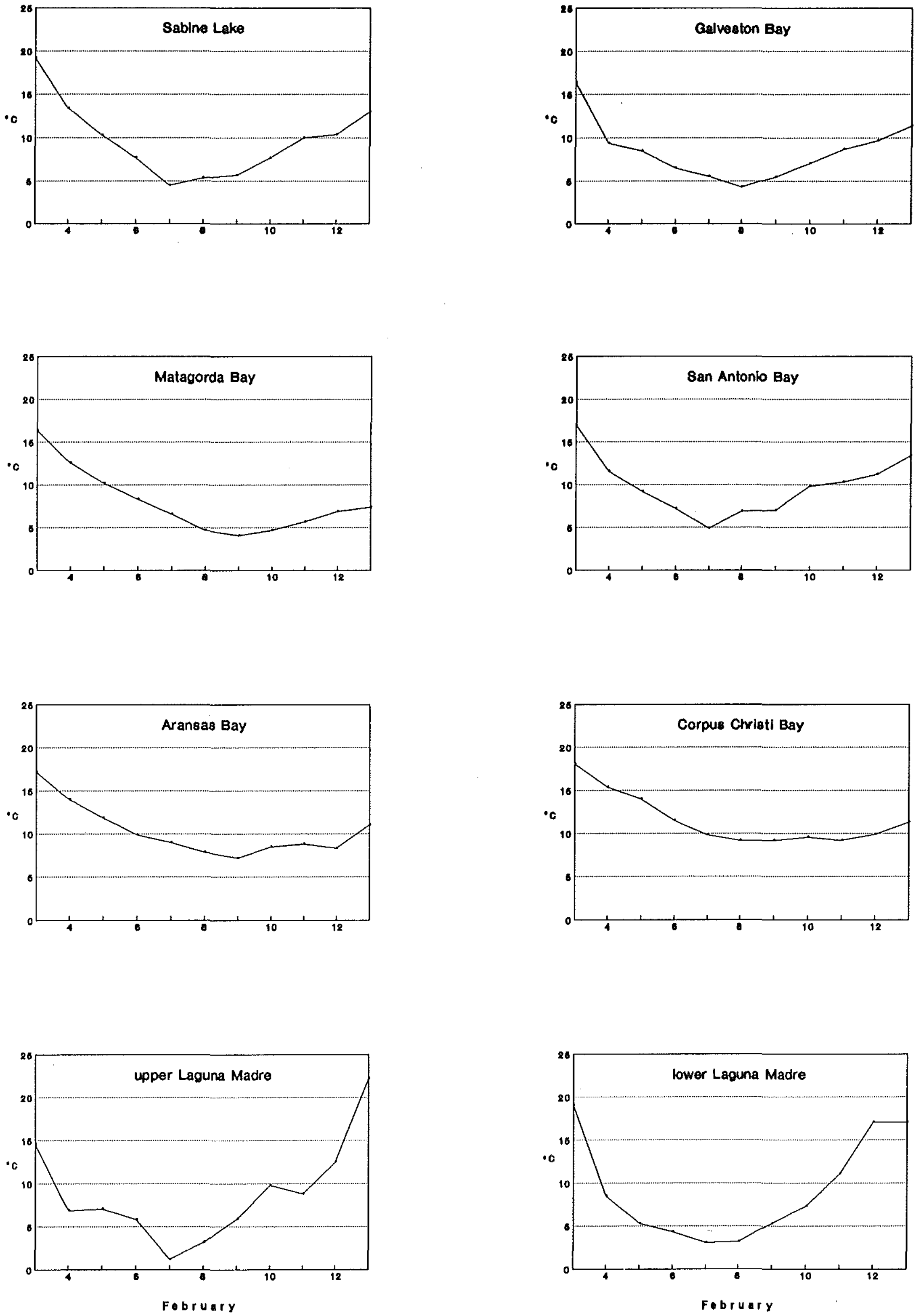

Figure 7. Daily mean water temperatures (°C) in Texas bays during February 1989.

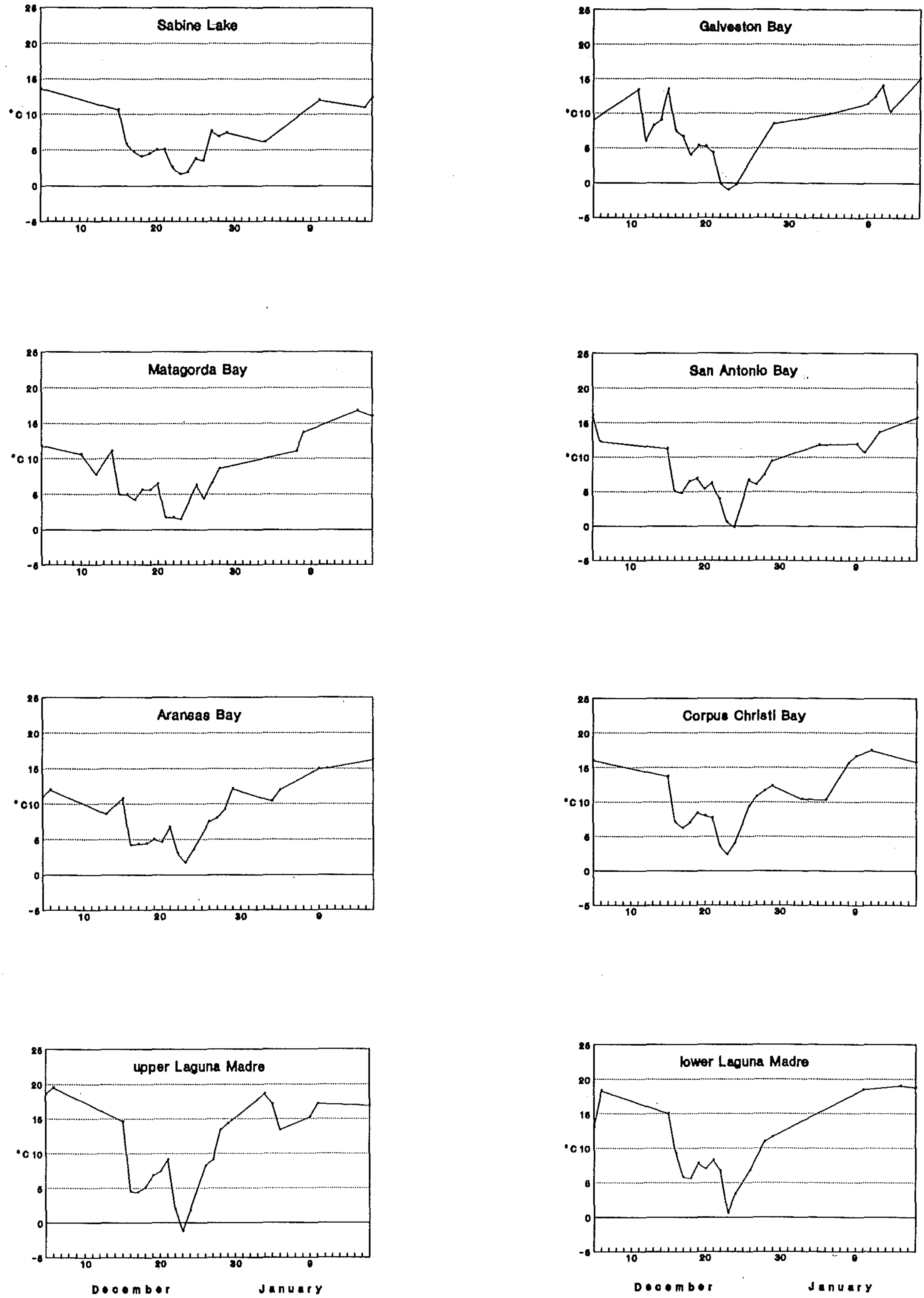

Figure 8. Daily mean water temperatures (°C) in Texas bays during December 1989.

stantially, depending on rapidity of temperature drop, severity and duration of cold, physiography characteristics of the affected area, and life history, behavior, and population dynamics of affected animals. The December 1983 freeze was the most severe of recent freezes, and one of the most severe in recorded Texas history. Water temperatures dropped about 15° C in about 10 days to near 0° C and remained between 0° and 5 ° for about 7 days. Fish that are most abundant in Texas bays during winter were the most numerous among the dead animals; most dead fish were seen in shallow bays on the southern (generally warmest) part of the coast. A similar pattern was observed in the December 1989 freeze; however, temperatures did not remain as low for as many days, and fewer fish were killed than in 1983. Even fewer fish were killed in February 1989 when lowest temperatures were generally higher than during the December freezes.

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