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Spatial and temporal distributions of contaminant body burden and disease in Gulf of Mexico oyster populations: The role of local and large-scale climatic controls

E. A. Wilson, E. N. Powell*, T. L. Wade, R. J. Taylor, B. J. Presley & J. M. Brooks

Department of Oceanography, Texas A & M University; College Station, TX 77843, USA

ABSTRACT: As part of NOAA's Status and Trends Program, oysters were sampled from 43 sites throughout the Gulf of Mexico from Brownsville, Texas, to the Florida Everglades from 1986 to 1989. Oysters were analysed for body burden of a suite of metals and petroleum aromatic hydrocarbons (PAHs), the prevalence and intensity of the oyster pathogen, *Perkinsus marinus*, and condition index. The contaminants fell into two groups based on the spatial distribution of body burden throughout the Gulf. Arsenic, selenium, mercury and cadmium were characterized by clinal reduction in similarity with distance reminiscent of that followed by mean monthly temperature and precipitation. Zinc, copper, PAHs and silver showed no consistent geographic trend. Within local regions, industrial and agricultural land use and *P. marinus* prevalence and infection intensity frequently correlated with body burden. Contaminants and biological attributes followed one of three temporal trends. Zinc, copper and PAHs showed concordant shifts over 4 years throughout the eastern and southern Gulf. Mercury and cadmium showed concordant shifts in the northwestern Gulf. Selenium, arsenic, length, condition index and *P. marinus* prevalence and infection intensity showed concordant shifts throughout most of the entire Gulf. Concordant shifts suggest that climatic factors, the El Niño/Southern Oscillation being one example, exert a strong influence on biological attributes and contaminant body burdens in the Gulf. Correlative factors are those that probably affect or indicate the rate of tissue turnover and the frequency of reproduction; namely, temperature, disease intensity, condition index and length.

INTRODUCTION

Bivalve molluscs have frequently been used as indicator organisms in studies monitoring levels of contaminants in the environment. These organisms are preferred because of their ability to accumulate and concentrate both metal and organic contaminants enabling them to serve as long-term integrators of their environment (Phillips, 1977a). However, many biological and environmental factors affect the rate and extent of bioaccumulation. Biological factors including differential growth rate (Cunningham & Tripp, 1975a; Boyden, 1977), reproductive stage (Cunningham & Tripp, 1975a; Frazier, 1975; Martincić et al., 1984), and general physiological condition, stress and disease

* Addressee for all correspondence

(Shuster & Pringle, 1969; Sindermann, 1983) affect incorporation and depuration rates. Similarly, changes in environmental parameters such as salinity (Denton & Burdon-Jones, 1981; Wright & Zamuda, 1987), freshwater runoff (Windom & Smith, 1972; Phillips, 1976a; Zaroogian & Cheer, 1976), duration of exposure to contaminants (Shuster & Pringle, 1969; Scott & Lawrence, 1982), temperature (Shuster & Pringle, 1969; Zaroogian & Cheer, 1976; Denton & Burdon-Jones, 1981), resuspension of sediments (Uncles et al., 1988) and proximity to point sources (Farrington & Quinn, 1973; Ratkowsky et al., 1974; Phillips, 1976b) can affect the bioavailability of environmental contaminants.

Although these local environmental and biological controls on variability in pollutant body burden are important; they, themselves, may be affected by long-term, large-scale phenomena such as climatic cycles. Such phenomena may override local controls and impose large-scale, concordant oscillations in environmental and biological parameters. Seasonal, climatic and other long-term cycles have been used in predicting harvests of commercially important fish and shellfish, including oysters (Dow, 1977; Ulanowicz et al., 1980; Allen & Turner, 1989), and have been implicated in the distribution and intensity of oyster disease (Powell et al., 1992). By imprinting themselves on the local environment, these long-term cycles may also alter the bioavailability of contaminants and, therefore, contaminant body burden. Accordingly, explaining spatial and temporal variability in contaminant body burden may require understanding both local and large-scale environmental phenomena.

The NOAA Status and Trends Program ("Mussel Watch") is an environmental monitoring program designed to monitor changes in environmental quality along the Atlantic, Pacific and Gulf coasts of the United States by measuring levels of chemical contaminants in fish, bivalves, and sediments and identifying biological responses to those contaminants. As part of the program, pollutant body burden of trace metals and polynuclear aromatic hydrocarbons (PAHs) were measured in oysters (*Crassostrea virginica*) collected from sites along the Gulf of Mexico coast from Brownsville, Texas to the Florida Everglades. The biological component of this study included determining the prevalence and intensity of infection by the endoparasitic protozoan *Perkinsus marinus* in these oyster populations. Over four years (1986–1989), this program has produced the most extensive spatial and temporal data set on contaminant body burden and disease prevalence and intensity available for natural oyster populations in the Gulf of Mexico and has implicated the El Niño/Southern Oscillation cycle as an important factor controlling large-scale temporal variability in oyster disease. The goal of this paper is to integrate the biological and chemical data to determine: (1) the spatial and temporal distributions of contaminant body burden as they compare to *P. marinus* in oyster populations; (2) the biological and environmental factors important in determining these distributions and (3) the role of local and long-term controls on contaminant body burdens.

MATERIALS AND METHODS

Sample collection

Oysters were collected from natural populations along the coast of the Gulf of Mexico during December to February of each year from 1986 to 1989. In all, 75 sites were sampled; 43 sites were sampled in all 4 years. Forty oysters were collected at each of three stations at each site; twenty for trace metal analysis and twenty for biological and trace organic analysis. Temperature and salinity were recorded at the time of collection.

The maximum anterior-posterior length was measured for each oyster (Morales-Alamo & Mann, 1989). Displacement volume of the 20 oysters collected for the biological and trace organic analyses was determined before and after shucking. Each oyster was sampled for the presence and intensity of infection by *Perkinsus marinus* (Ray, 1966). Prevalence of infection was calculated as: (the number of infected oysters/number of oysters sampled). Infection intensity was ranked on the 0-to-5-point scale of Mackin (1962) as modified by Craig et al. (1989). After the biological sample was removed, the remainder of the oyster tissue was placed in precombusted jars, sealed with Teflon lids, weighed and frozen for trace organic analysis. Tissue dry weight and displacement volume were used to calculate condition index = dry weight of tissue/internal volume of shell cavity (Scott & Lawrence, 1982). The twenty oysters collected for trace metal analysis were scrubbed, frozen in the shell and returned to the laboratory. Further sample preparation and the analytical techniques employed for both trace organic and trace metal analyses were described in Brooks et al. (1989).

Statistical analysis

Data reduction

Within-site variability was typically low (Craig et al., 1989; Wilson et al., 1990), so the three stations were combined for the following statistical analyses. Statistical analysis of the data was limited to the 43 sites sampled in each of the 4 years. Each site was assigned to one of 26 bay systems as slightly modified from Broutman & Leonard (1988) (Table 1) [see Craig et al. (1989) or Presley et al. (1990) for site maps, and Wilson et al. (1990) and Powell et al. (in press) for further information on the sites]. Salinity and temperature data for the sites are given in Brooks et al. (1989). Powell et al. (1992) list mean *P. marinus* prevalences and infection intensities for the bay groups. Mean values of condition index and length for the bay groups are presented in Table 2.

Seven of the 13 metals analysed as part of the Status and Trends protocol were chosen for further consideration: arsenic, cadmium, copper, silver, mercury, zinc and selenium. These metals were selected because they generally were present in highest concentration among the metals measured and because they exhibited some of the most dramatic differences in body burdens in populations around the Gulf of Mexico and among the 4 years of the study. Wade et al. (1988) and Brooks et al. (1989) list the individual PAHs analysed, but, for this study, body burdens of the individual PAHs were summed and a total value was used for statistical analysis. Contaminant data are presented as the geometric mean of all sites included in each bay group (Tables 3, 4 and 5).

Values for mean monthly precipitation and mean monthly temperature were obtained from NOAA (1985–1989). The values used were averages of several stations around each bay system. Average monthly stream flow from gauged streams – Rio Grande (IBWC, 1985–1989), the Mississippi and Atchafalaya Rivers (Army Corps of Engineers, personal communication) and the remaining gauged rivers and streams (USGS, 1985–1989) – and estimated freshwater runoff (from precipitation data) for areas downstream of gauges, estimated from the total watershed area (NOAA, 1987), were summed to estimate total freshwater input to each bay system. Land use around the bay systems, classified as either industrial, agricultural or residential, was compiled from NOAA (1987).

Table 1. Site names, four-letter site designations, locations and assignments into bay groups for the 43 Status and Trends sites sampled in all 4 years of the study

Bay group	Site name	Site designation	Location Latitude		Location Longitude	
	Texas					
1	Laguna Madre, South Bay	LMSB	26	2.58	97	10.49
2	Corpus Christi Bay, Nueces Bay	CCNB	27	51.70	97	21.00
3	Aransas Bay, Long Reef	ABLR	28	3.30	96	57.50
	Copano Bay, Copano Reef	CBCR	28	8.20	97	7.58
	Mesquite Bay, Ayres Reef	MBAR	28	10.30	96	49.70
5	Matagorda Bay, Gallinipper Point	MBGP	28	35.00	96	34.00
	Matagorda Bay, Tres Palacios Bay	MBTP	28	39.00	96	15.50
6	East Matagorda Bay	MBEM	28	42.30	95	53.00
8	Galveston Bay, Yacht Club Reef	GBYC	29	37.00	94	59.50
	Galveston Bay, Todd's Dump Reef	GBTD	29	30.10	94	54.00
	Galveston Bay, Hanna Reef	GBHR	29	27.50	94	42.50
	Galveston Bay, Confederate Reef	GBCR	29	15.75	94	50.50
9	Sabine Lake, Blue Buck Point	SLBB	29	48.00	93	54.42
	Louisiana					
10	Lake Calcasieu, St. Johns Island	CLSJ	29	50.00	93	23.00
11	Joseph Harbor Bayou	JHJH	29	37.75	92	45.75
12	Vermillion Bay, Southwest Pass	VBSP	29	34.70	92	4.00
13	Atchafalaya Bay, Oyster Bayou	ABOB	29	13.00	91	8.00
	Caillou Lake	CLCL	29	15.25	90	55.50
14	Lake Barre	TBLB	29	15.00	90	36.00
	Lake Felicity	TBLF	29	16.00	90	24.50
15	Barataria Bay, Bayou St. Denis	BBSD	29	24.10	89	59.80
	Barataria Bay, Middle Bank	BBMB	29	17.20	89	56.50
18	Breton Sound, Bay Garderne	BSBG	29	35.87	89	38.50
	Breton Sound, Sable Island	BSSI	29	24.70	89	28.70
19	Lake Borgne, Malheureux Point	LBMP	29	52.30	89	40.70
	Mississippi					
20	Mississippi Sound, Pass Christian	MSPC	30	19.75	89	19.58
	Biloxi Bay	MSBB	30	23.38	88	55.42
	Pascagoula Bay	MSPB	30	21.05	88	37.00
	Alabama					
21	Mobile Bay, Cedar Point Reef	MBCP	30	19.40	88	7.30
	Florida					
22	Pensacola Bay, Indian Bayou	PBIB	30	30.83	87	4.00
23	Choctawhatchee Bay, Santa Rosa	CBSR	30	23.50	86	10.60
	Choctawhatchee Bay, Shirk Point	CBSP	30	28.95	86	28.60
24	St. Andrew Bay, Watson Bayou	SAWB	30	8.50	85	37.58

Table 1 (Continued)

Bay group	Site name	Site designation	Location Latitude		Location Longitude	
	Florida					
25	Apalachicola Bay, Dry Bar	APDB	29	41.50	85	5.00
	Apalachicola Bay, Cat Point Bar	APCP	29	43.00	84	52.50
27	Cedar Key, Black Point	CKBP	29	10.25	83	3.00
	Tampa Bay, Papys Bayou	TBPB	27	50.72	82	36.75
28	Tampa Bay, Cockroach Bay	TBCB	27	40.55	82	30.56
	Tampa Bay, Mullet Key Bayou	TBMK	27	37.28	82	43.62
29	Charlotte Harbor, Bird Island	CBBI	26	31.00	82	2.60
30	Naples Bay	NBNB	26	7.00	81	47.10
	Rookery Bay, Henderson Creek	RBHC	26	1.83	81	43.75
31	Everglades, Faka Union Bay	EVFU	25	54.27	81	30.60

Table 2. Arithmetic means for condition index (g cm^{-3}) and length (cm) for the 26 bay groups for each of the 4 years of the study. Means are determined from all sites within each designated bay group

Bay group	Condition index 1986	Condition index 1987	Condition index 1988	Condition index 1989	Length 1986	Length 1987	Length 1988	Length 1989
1	0.086	0.076	0.122	0.115	8.163	6.953	6.035	6.028
2	0.087	0.131	0.110	0.065	7.407	5.673	5.521	7.042
3	0.092	0.141	0.104	0.098	8.470	8.197	8.187	6.383
5	0.099	0.137	0.114	0.075	9.378	8.299	6.916	7.071
6	0.087	0.119	0.100	0.099	10.132	8.370	6.717	6.292
8	0.106	0.119	0.109	0.052	9.032	8.556	8.546	8.332
9	0.075	0.130	0.088	0.043	10.440	9.648	9.655	8.395
10	0.100	0.108	0.135	0.054	11.477	8.265	7.988	9.323
11	0.120	0.126	0.081	0.112	8.358	8.787	8.187	7.062
12	0.108	0.097	0.088	0.081	8.715	9.658	9.908	9.057
13	0.105	0.112	0.122	0.051	9.731	10.360	8.182	8.197
14	0.096	0.106	0.107	0.071	8.961	9.223	7.178	7.488
15	0.088	0.114	0.125	0.068	10.079	9.566	7.040	6.861
18	0.165	0.103	0.113	0.058	9.657	8.504	7.708	8.465
19	0.097	0.128	0.125	0.053	8.942	7.270	7.524	5.682
20	0.119	0.112	0.144	0.093	8.399	7.153	7.104	7.204
21	0.144	0.105	0.113	0.096	8.622	9.003	6.033	6.663
22	0.109	0.135	0.144	0.081	9.090	4.558	6.017	6.456
23	0.119	0.122	0.091	0.063	7.747	4.949	6.673	5.974
24	0.141	0.150	0.140	0.089	6.008	4.810	6.528	6.347
25	0.149	0.109	0.119	0.102	8.433	7.347	8.286	6.637
27	0.159	0.104	0.106	0.089	7.438	5.515	6.714	5.390
28	0.087	0.120	0.117	0.086	6.578	5.898	6.373	6.443
29	0.081	0.109	0.179	0.061	6.517	5.295	6.466	6.640
30	0.116	0.108	0.162	0.078	6.702	5.262	4.673	5.469
31	0.123	0.125	0.022	0.054	8.060	6.560	6.558	5.835

Table 3. Geometric means of pollutant body burden for the metals silver, arsenic, cadmium and selenium for each bay group and each year of the study. Values given are parts per million (ppm)

	Pollutant body burden															
Bay	Silver				Arsenic				Cadmium				Selenium			
group	1986	1987	1988	1989	1986	1987	1988	1989	1986	1987	1988	1989	1986	1987	1988	1989
1	1.73	1.14	0.88	1.68	21.67	15.10	18.67	14.84	3.83	2.72	2.13	2.64	2.87	2.13	4.66	2.49
2	1.38	1.80	1.91	1.48	10.95	10.63	10.66	8.20	6.30	11.88	4.74	4.32	2.68	2.35	5.15	4.03
3	4.05	2.08	2.79	2.63	7.47	6.36	6.37	7.14	7.63	5.14	6.34	5.73	4.43	2.79	5.61	3.87
5	1.87	1.62	3.10	2.65	8.24	5.88	7.99	9.37	4.57	3.90	4.84	5.16	2.63	2.45	4.82	3.07
6	4.67	5.14	2.50	2.59	8.33	5.77	5.93	6.84	7.33	6.61	4.70	5.38	4.07	3.50	4.57	3.95
8	1.76	2.39	2.24	2.35	4.81	4.88	3.48	4.44	4.33	4.11	3.16	5.00	3.04	3.07	4.04	3.34
9	2.69	7.13	4.60	3.29	5.50	4.10	5.50	5.80	4.17	7.16	4.36	5.13	2.53	2.68	4.07	2.84
10	2.00	2.19	2.45	1.74	10.33	6.60	4.37	5.91	4.33	5.08	3.49	3.88	2.30	2.25	3.66	3.31
11	2.57	3.16	2.90	2.29	8.00	7.97	4.80	5.63	4.83	3.61	4.57	5.09	2.13	3.48	3.52	4.37
12	5.00	4.55	3.47	5.08	9.67	8.50	4.67	6.13	9.67	9.25	6.43	10.39	2.23	4.37	5.43	4.44
13	1.04	1.61	2.01	1.67	10.09	7.14	7.20	5.69	3.34	5.28	4.84	5.55	1.78	2.61	3.27	3.17
14	0.43	0.51	0.93	0.68	10.25	8.78	7.39	4.98	1.98	2.29	3.69	3.13	1.54	2.22	5.16	2.21
15	0.36	0.73	1.23	0.77	9.75	10.77	7.89	7.55	1.44	1.46	2.17	2.17	1.03	1.75	3.58	2.24
18	1.07	0.95	1.49	0.91	6.83	9.28	10.22	6.34	2.99	6.76	7.04	5.10	1.85	2.75	3.89	2.36
19	1.83	0.78	1.49	1.47	6.33	4.27	4.90	4.46	5.43	5.26	5.68	6.13	2.57	2.32	4.29	2.59
20	3.29	2.03	2.12	2.79	14.96	9.66	14.30	8.14	4.14	3.79	3.87	4.07	2.09	2.61	3.41	2.43
21	2.20	1.84	1.98	2.01	15.66	6.33	7.04	6.45	2.50	2.38	3.56	3.75	1.63	1.78	2.34	1.77
22	1.33	2.80	1.66	1.50	11.33	17.20	12.14	8.84	3.87	2.83	2.86	2.74	2.40	2.13	3.42	2.29
23	3.99	2.49	2.79	1.69	6.71	8.01	6.21	9.35	3.57	2.51	4.29	3.09	3.27	3.62	5.87	4.25
24	1.70	1.67	1.64	1.85	15.67	12.97	17.48	12.42	1.13	1.16	1.06	1.35	1.20	1.68	2.76	2.34
25	1.72	2.62	1.76	1.26	10.05	11.93	11.54	9.89	2.87	2.59	2.55	2.12	1.61	1.99	3.27	2.05
27	0.33	0.45	0.42	1.12	39.00	23.70	18.86	18.90	2.10	1.72	2.44	3.11	1.37	2.43	2.05	3.89
28	0.90	1.15	0.85	1.08	7.32	6.66	8.66	7.26	2.29	2.24	2.97	2.34	1.36	2.09	2.39	1.71
29	1.53	3.38	1.27	2.13	38.67	31.13	11.67	14.76	3.90	4.06	3.01	2.86	1.70	2.63	1.77	1.91
30	2.51	2.98	3.26	2.18	24.52	27.97	28.16	19.28	2.02	1.38	1.81	1.43	1.49	2.20	2.09	1.61
31	0.70	1.39	0.77	1.29	8.83	7.63	7.47	7.97	3.20	1.83	2.20	2.27	1.87	1.97	2.37	2.51

Table 4. Geometric means of pollutant body burden for the metals copper, zinc and mercury for each bay group and each year of the study. Values are given in parts per million (ppm)

Bay group	Copper 1986	Copper 1987	Copper 1988	Copper 1989	Zinc 1986	Zinc 1987	Zinc 1988	Zinc 1989	Mercury 1986	Mercury 1987	Mercury 1988	Mercury 1989
1	120.00	120.33	169.84	130.08	1633.33	1257.67	4945.86	1621.72	130.00	196.67	100.14	184.16
2	110.55	162.33	191.61	111.18	3343.98	3260.00	4346.31	4157.87	79.86	22.00	136.25	122.36
3	172.61	98.45	197.68	113.84	1211.01	724.60	1304.14	1286.43	105.69	54.11	142.06	104.43
5	116.01	106.22	182.32	233.00	1137.03	941.69	1382.09	1700.61	173.69	106.27	148.58	223.72
6	190.00	127.67	214.00	238.39	883.33	3127.00	1072.67	1292.25	67.67	77.33	69.00	78.57
8	121.57	161.71	156.76	193.06	2186.77	2544.19	3186.98	3438.99	56.93	92.16	47.31	90.61
9	90.00	493.67	272.33	220.52	8000.00	5989.00	4146.67	3370.99	143.33	146.67	108.33	98.29
10	183.33	180.00	276.58	185.80	2600.00	1899.33	3093.52	2345.64	111.67	89.33	98.20	98.19
11	173.33	182.67	170.00	192.22	1200.00	1324.33	1625.67	2129.86	47.67	50.33	70.00	92.56
12	353.33	509.33	248.67	611.67	2300.00	2896.67	1435.33	4089.20	39.00	77.67	38.33	61.51
13	105.28	186.84	163.18	148.00	1264.91	2353.74	2143.93	1783.13	32.44	46.47	45.34	55.75
14	63.89	75.52	114.35	86.43	1568.44	1578.96	2104.39	2388.97	43.72	77.81	87.49	77.66
15	39.28	86.93	134.88	71.44	916.67	2097.02	2593.78	2625.89	43.72	77.81	87.49	77.66
18	92.49	105.32	95.16	67.39	1052.78	1491.33	1205.69	993.89	32.79	108.78	52.28	64.38
19	293.33	116.00	281.99	228.19	3400.00	1285.00	3433.15	3169.99	33.33	153.33	124.37	89.47
20	128.52	146.79	172.63	208.14	3215.66	3229.64	2762.19	4555.68	130.52	136.36	113.76	156.95
21	100.00	59.33	133.86	132.51	916.67	956.00	1891.42	1957.27	70.00	67.67	73.71	61.09
22	75.00	43.33	65.60	53.19	2133.33	470.00	1572.89	1356.49	243.33	84.33	119.58	121.23
23	77.28	54.89	99.86	114.03	2178.69	1983.16	3331.22	2170.02	256.48	296.37	233.33	267.79
24	416.67	279.67	210.71	139.86	5400.00	3316.00	3150.72	3657.02	71.67	43.00	71.40	132.34
25	54.21	41.16	49.67	71.32	530.72	333.13	356.36	529.04	117.36	100.43	74.09	113.84
27	14.67	20.33	18.07	38.64	300.00	483.00	916.73	488.35	106.67	138.00	139.02	91.03
28	68.06	52.83	67.33	74.37	1666.15	1211.38	1859.14	2026.37	230.97	196.97	239.87	213.37
29	85.00	153.00	103.36	153.71	1300.00	1679.67	1706.11	2695.68	313.33	296.67	188.36	234.87
30	149.40	237.02	202.52	189.99	1302.35	1827.04	2089.41	1963.47	187.08	164.92	137.15	151.44
31	44.67	40.33	48.33	69.88	933.33	864.67	1167.67	1133.40	246.67	190.00	155.00	181.52

Table 5. Geometric means of pollutant body burdens for total polynuclear aromatic hydrocarbons (PAH). Values are given for each bay group and each year of the study in parts per billion (ppb)

	PAH body burden			
Bay group	1986	1987	1988	1989
1	24.50	20.00	314.22	48.00
2	57.89	417.00	969.89	408.85
3	52.54	24.10	106.16	29.67
5	41.25	79.48	93.97	75.12
6	90.67	64.67	29.67	202.67
8	248.19	233.97	275.68	319.59
9	219.33	58.33	171.67	172.67
10	385.33	63.33	252.46	364.41
11	41.33	162.00	28.00	82.67
12	68.67	88.67	51.67	30.00
13	153.33	61.65	57.04	81.99
14	213.92	29.77	354.18	204.29
15	257.28	241.21	147.85	2670.34
18	203.63	65.41	263.38	131.48
19	74.00	34.67	89.63	101.50
20	471.57	687.38	468.32	453.26
21	72.67	333.33	535.73	214.97
22	435.67	187.67	313.99	139.03
23	298.80	940.56	1121.29	398.74
24	13277.67	2709.67	2533.99	961.36
25	52.02	22.33	1334.12	1025.00
27	38.33	44.33	380.11	72.50
28	144.93	72.73	111.36	176.94
29	20.67	201.67	84.85	509.35
30	100.18	51.77	68.90	134.98
31	98.00	20.00	196.67	108.00

Spatial distribution

The spatial distribution of each contaminant was examined using a spatial autocorrelation method described by Cliff & Ord (1973). We used Moran's I as the test statistic, where:

$$I = (n/W)\frac{\sum_{i=1}^{n}\sum_{\substack{j=1 \\ i \neq j}}^{n} w_{ij} z_i z_j}{\sum_{i=1}^{n} z_i^2}$$

and

$$W = \sum_{i=1}^{n}\sum_{\substack{j=1 \\ i \neq j}}^{n} w_{ij};\ z = x_i - \bar{x};$$

n = number of samples, x_i = value of each sample and w_{ij} = a weighting measure as described below.

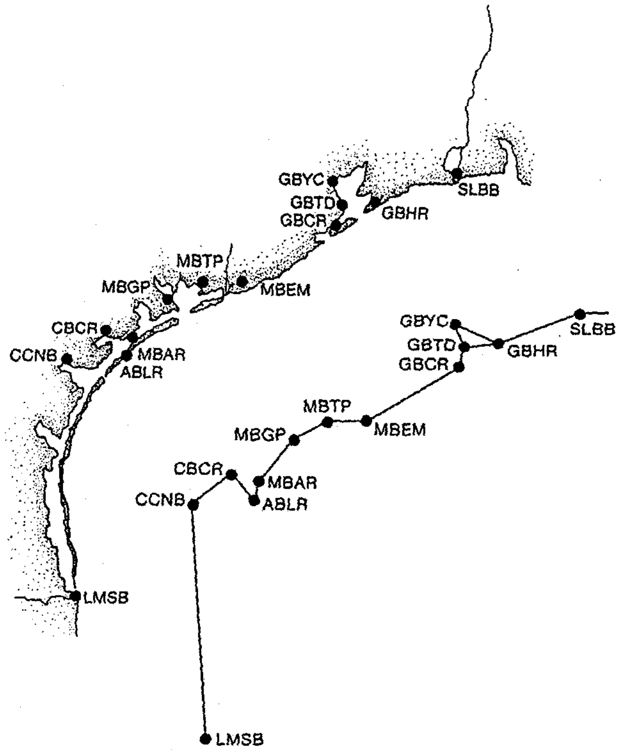
Moran's I is sensitive to the location of extreme departures from the mean ($x_i - \bar{x}$). For example, in a patchy distribution, adjacent samples would both tend to be much above or below the mean more frequently than would be expected by chance. Significance levels were calculated after Jumars et al. (1977) under the assumption of randomization. Cliff & Ord (1973) showed, for samples that are spatially randomly distributed, that the expected value of I is $-(n-1)^{-1}$. Hence, values of I below $-(n-1)^{-1}$ indicate negative spatial autocorrelation (an even distribution) and values above $-(n-1)^{-1}$ positive spatial autocorrelation (a patchy distribution).

The use of this technique depends upon the choice of a weighting system (w_{ij}) which is a mathematical expression of the spatial relationship between the sampled sites. Factors involved in the choice of a weighting system were discussed by Jumars et al. (1977), Sokal & Oden (1978a) and Cliff & Ord (1973). We constructed a Gabriel-connected graph (Gabriel & Sokal, 1969) for the bays sampled in all 4 years. In this case, two sites ($\overline{AB}$) were connected if no third site (C) existed that formed an obtuse angle when connected between the other two ($\sphericalangle$ ACB). Gabriel-connected pairs were given a weight (w_{ij}) of 1.0 and all other pairs $w_{ij} = 0$ (Fig. 1).

The change in spatial relationship among samples at varying distances can be used to identify the scale of spatial variation. For example, in a patchy population, samples closer than patch size will be more similar than expected by chance [e.g. Moran's I $> -(n-1)^{-1}$], whereas samples further apart than patch size will be less similar [e.g. Moran's I $< -(n-1)^{-1}$]. We examined the change in spatial relationship with distance using correlograms (plots of sample similarity versus distance between samples) calculated as discussed by Sokal & Oden (1978a, b). Distances were calculated along the Gabriel network by Marble's method (1967). Bays within a given distance from one another when joined along the Gabriel network were given $w_{ij} = 1.0$; for all others $w_{ij} = 0$. Therefore, our correlograms were distance-corrected using the terminology of Sokal & Oden (1978a).

Temporal changes in spatial distribution

To examine the spatial scale of yearly changes in the biological variables and contaminant body burdens and to determine whether concordant changes occurred among several variables, we used the analytical approach of Powell et al. (1984) as adapted by Powell et al. (1992). First, we ranked each of the 4 years for each bay group from 1 (highest) to 4 (lowest) for prevalence and mean infection intensity of *P. marinus*, length, condition index and each of the eight contaminants. Two bays or two parameters were compared by subtracting each year's rank for one from the corresponding rank for the other and summing the absolute value of the 4 differences. As an example, if the data for bay group 1 were ranked 1, 2, 3, and 4 for the 4 years and the data for bay group 2 were ranked 1, 3, 2, and 4, then the differences would be 0, −1, 1, 0 and the absolute value of the sum would be 2. The values of the sums obtained in this way can only take the values 0, 2, 4, 6, and 8. The frequency spectrum of occurrences of the possible sums between site pairs having randomly distributed ranks is 0 (.042), 2 (.125), 4 (.292), 6 (.375) and 8 (.167). A frequency spectrum of sums calculated from the data in this way was compared to the frequency expected by chance combinations of the rankings using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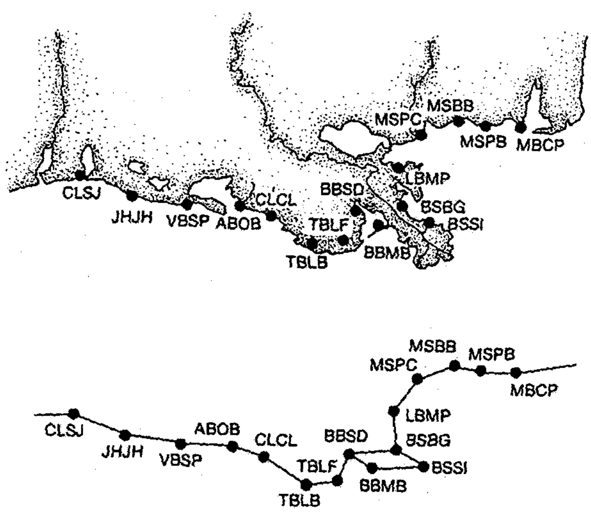
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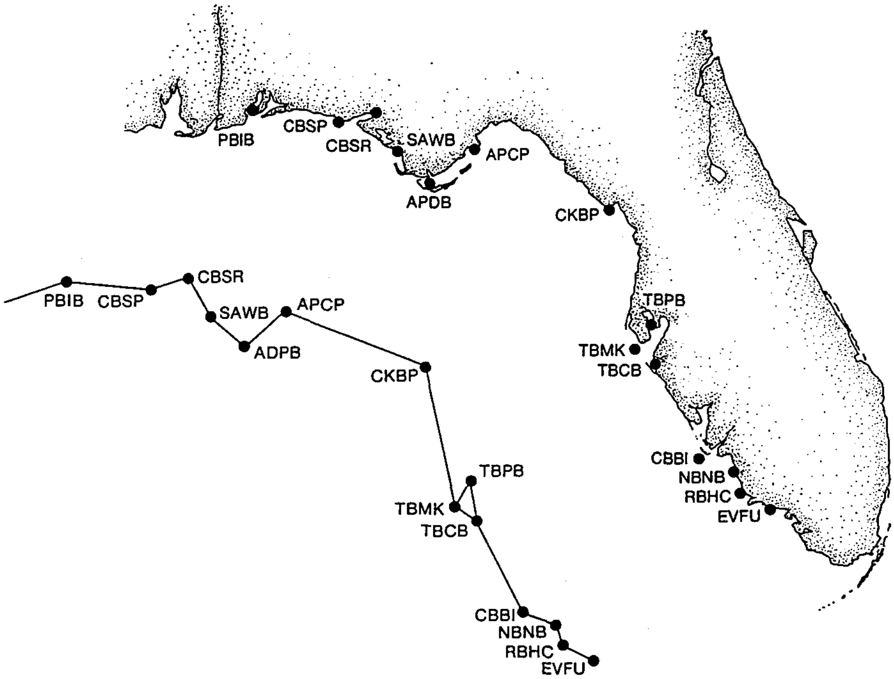


Fig. 1. Distance-corrected Gabriel graphs for the sites sampled around the Gulf of Mexico in each of the 4 years of the Status and Trends Program. Four-letter site designations correspond with those in Table 1. Dots indicate site locations. Graph is drawn opposite for clarity. See Powell et al. (1992) for more details

Kolmogorov-Smirnov (K-S) one-sample two-sided tests. Significance of the K-S statistic was judged using Conover's (1972) method for calculating exact P-values for discrete data. In this analysis, if the year-to-year change in any variable between bay systems tended to co-vary, most going up or most going down, then values of 0 or 2 in the previous example would occur more frequently than expected by chance. If the yearly changes tended to oppose one another (for example some bays going up, the others down) then values of 8 would be frequently obtained.

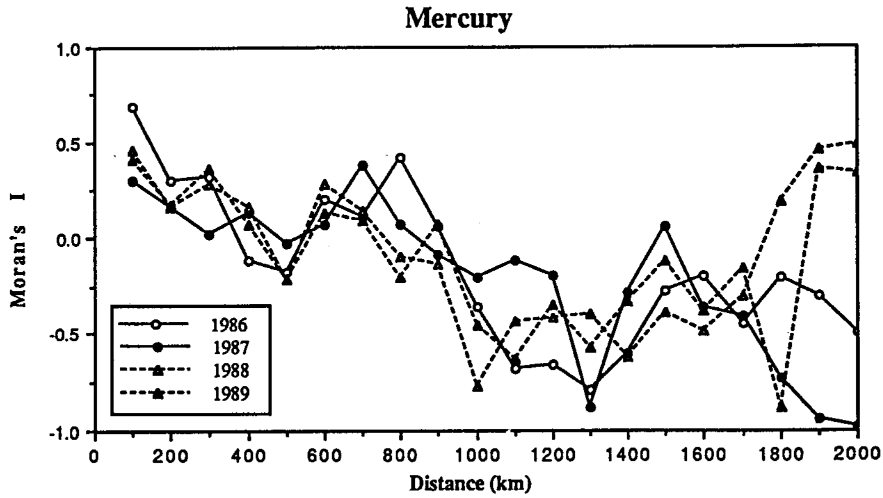
We utilized the preceeding approach on two geographical scales, the entire Gulf of Mexico (all bay systems) and sets of ten contiguous bay systems, contiguous being defined along the Gabriel graph. In the latter case, 10 bay systems were chosen because the number of bay systems in Texas and extreme western Louisiana, as defined here, was 10. To determine the extent of regional similarity, sets of ten bay systems were examined step by step around the Gulf of Mexico in the following manner. Step one always compared bays from the Laguna Madre in south Texas through Vermillion Bay in western Louisiana. Step 2 was generated by deleting the most southern bay system (Laguna Madre) and adding the next bay system to the east (Atchafalaya Bay and Caillou Lake). Consecutive steps followed the same protocol with one exception. Steps originating on the eastern Gulf coast were allowed to wrap around the Gulf. For example, step 22 compared the five southernmost Florida bay systems (Cedar Key to the Everglades) and the 5 southernmost bay systems in Texas (Laguna Madre through East Matagorda Bay). We examined all possible pair-wise combinations within the set of 10 bay systems. This generated 45 sums. The frequency of these sums was compared against the expected frequency of sums using K-S tests as previously described. A non-significant value for the K-S statistic among the 10 bay systems making up one step indicates local control of the temporal variation in the variable (e.g. pollutant body burden, disease). In other words, coincident oscillations (two bay systems simultaneously going up or down in value) from one year to the next did not occur among the 10 bay systems more frequently than expected by chance over the spatial scale encompassing the 10 bay systems. This result would suggest no regional imprint on local control of variability. Similarly, a significant value of the K-S statistic would suggest that regional influences overrode local controls so that temporal variation, in contaminant body burden or disease for example, was substantially affected by climatic, as well as local, factors. Plots of the K-S statistic as a function of steps around the Gulf give a graphical representation of the spatial extent of this similarity.

Within those geographic regions where yearly changes in pollutant body burden were concordant using the K-S test, R^2 improvement tests were conducted to determine the factors that might have produced the observed concordancy. Factors tested in most models included length, condition index, mean temperature, mean precipitation, *P. marinus* prevalence and infection intensity, and agricultural and industrial land use. The parameters that produced the best R^2 model were then used in regression analysis, again only in regions of yearly concordancy as defined by consecutive significant results of the K-S test. Not knowing the response times for pollutant body burdens to shifts in environmental regimes in most cases, analyses were conducted using the average precipitation and temperature values for the 5 months prior to sampling and the 2 months prior to sampling. Prevalence and infection intensity of *P. marinus* were used in R^2-improvement and regression analyses only with the average precipitation and temperature data for the 2 months prior to sampling because *P. marinus* responds so rapidly to changes in the environmental regime.

RESULTS

Spatial distribution, Gulf-wide

Correlograms calculated along the Gabriel network for the distribution of contaminant body burden with distance around the Gulf of Mexico are given in Figures 2 to 5. The contaminants can be divided into two distinct groups. For mercury, selenium, arsenic and cadmium, site-to-site similarity gradually declines with distance over the first approximately 1600 km in each of the 4 years. The correlograms pass through $I = -(n-1)^{-1}$ at about 400 km. That is, bay groups less than 400 km apart are more similar in body burden of these metals than expected by chance and sites become less and less similar at larger and larger spatial scales. Another characteristic of the distribution of group 1 contaminants is the close association between the first 2 years (1986 and 1987) and the last 2 years (1988 and 1989) at the longest spatial scales. Body burden of oysters from the east and west coasts of the Gulf varied similarly among the bays within both pairs of years and



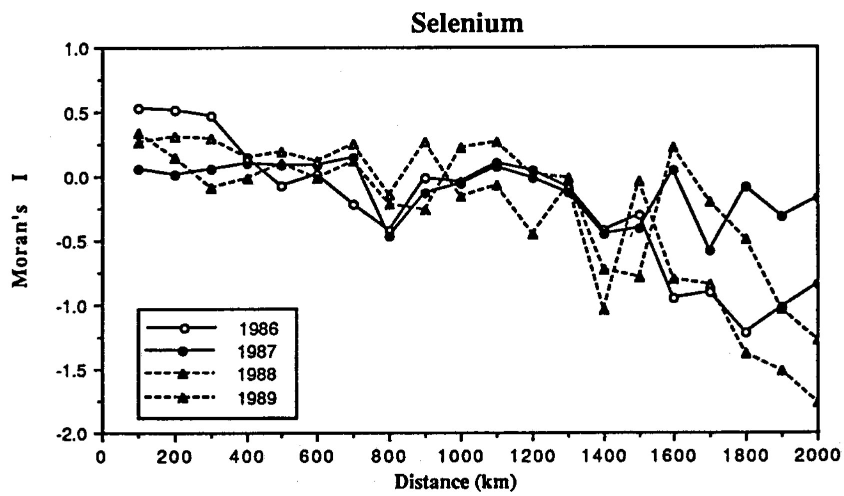
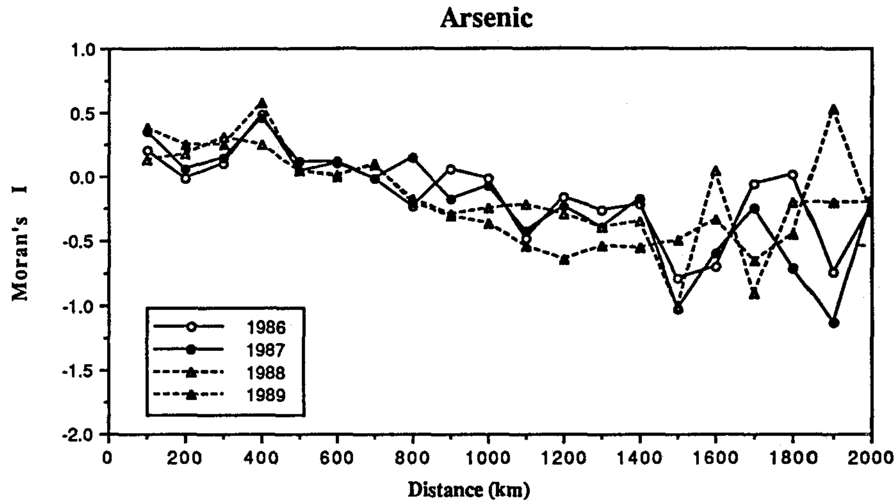


Fig. 2. Correlograms relating distance (km) to Moran's I obtained using body burden of mercury and selenium for all sites sampled in each year. Distances were calculated along the Gabriel network, where stations separated by, for example, 101 and 200 km were used to generate the 200-km point. The ideal random value for Moran's I is approximately −0.04

were affected similarly by some large-scale event which occurred between 1987 and 1988.

In contrast to group 1 contaminants, the distribution of group 2 contaminants, copper, zinc, silver and total PAHs, shows no overall trend; rather the pattern tends to oscillate about the ideal random value at most spatial scales for all 4 years. This pattern also does not clearly show the distinct break between 1986–1987 and 1988–1989.

Perkinsus marinus is an important pathogen in oyster populations in the Gulf of Mexico, and is responsible for high mortality in most years (Hofstetter, 1977). Correlo-



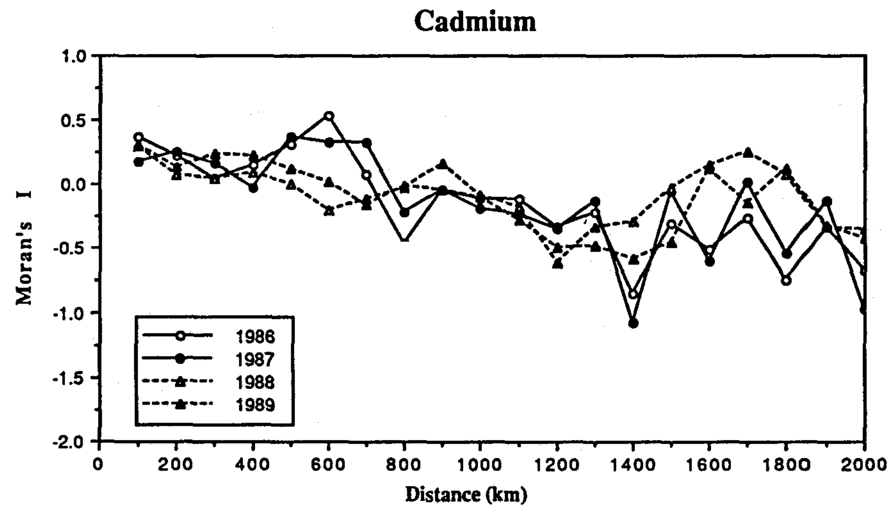


Fig. 3. Correlograms relating distance (km) to Moran's I obtained using body burden of arsenic and cadmium for all sites sampled in each year. Distances were calculated along the Gabriel network, where stations separated by, for example, 101 and 200 km were used to generate the 200-km point. The ideal random value for Moran's I is approximately −0.04

grams for mean prevalence and mean infection intensity of *P. marinus* for each of the 4 years are given in Powell et al. (1992). Overall, the spatial distribution of *P. marinus* prevalence and infection intensity, while not identical, retains many of the spatial characteristics of group 1 contaminants. Correlograms for *P. marinus* prevalence and infection intensity demonstrate a very strong relationship between year pairs 1986/87 and 1988/89. Again, the break between 1987 and 1988 results in two very different distributional patterns at certain spatial scales. Similarity declines over the first approxi-

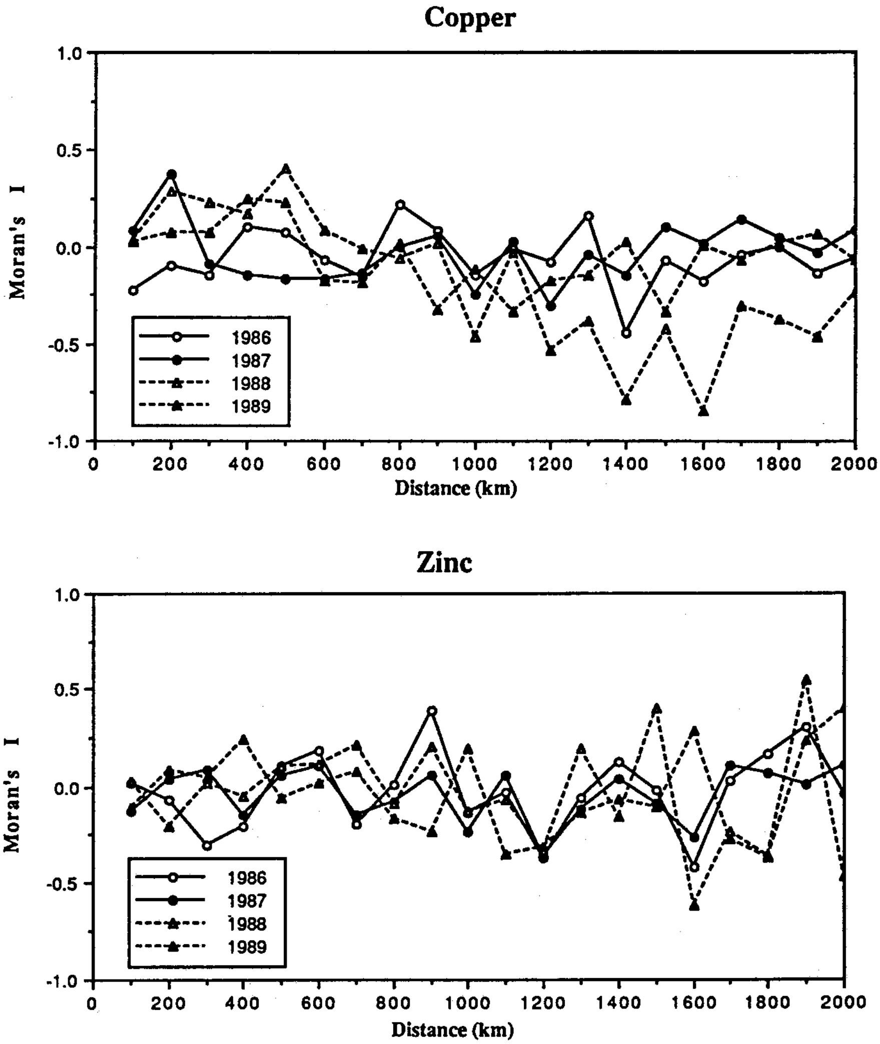
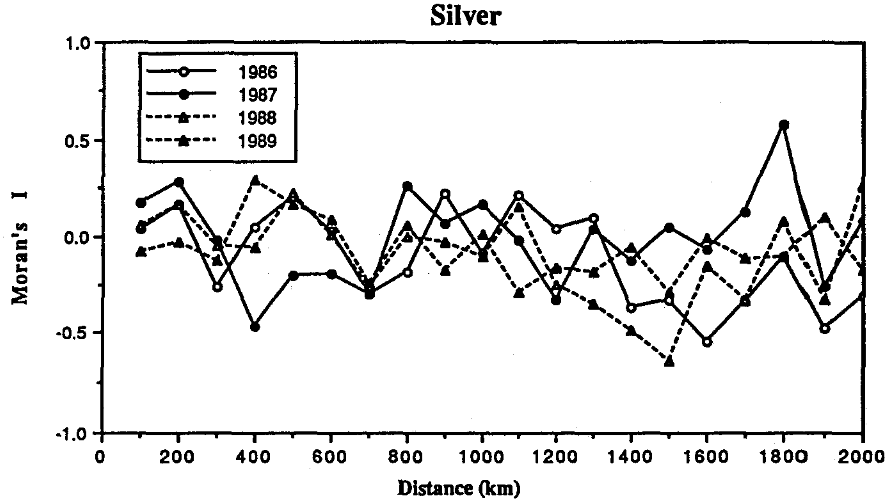


Fig. 4. Correlograms relating distance (km) to Moran's I obtained using body burden of copper and zinc for all sites sampled in each year. Distances were calculated along the Gabriel network, where stations separated by, for example, 101 and 200 km were used to generate the 200-km point. The ideal random value for Moran's I is approximately −0.04

mately 1400 km, although more rapidly than it does for the contaminants, and returns again at longer spatial scales.

Temporal changes in spatial distribution

Utilizing first the spatial scale of the Gulf of Mexico (>2000 km along the Gabriel network), few contaminants had significantly concordant shifts (Table 6). For selenium,



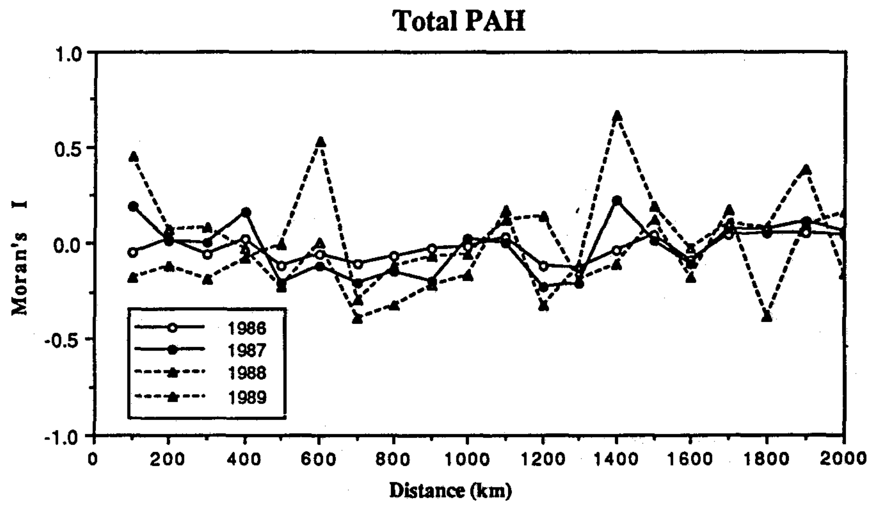


Fig. 5. Correlograms relating distance (km) to Moran's I obtained using body burden of silver and total PAH for all sites sampled in each year. Distances were calculated along the Gabriel network, where stations separated by, for example, 101 and 200 km were used to generate the 200-km point. The ideal random value for Moran's I is approximately −0.04

and to a lesser extent zinc, copper and arsenic, however, many more bay systems in the Gulf tended to vary similarly year-to-year than would be expected by chance. That is, the tissue concentration of these contaminants tended to increase or decrease uniformly from one year to the next in all or a significant portion of the bay systems. Such coincident shifts in body burden would indicate some regional or Gulf-wide control on body burden. Among the biological indices, condition index, length, *Perkinsus marinus* prevalence and

Table 6. Results of analyses to detect concordant temporal shifts among all 26 bay systems in the Gulf of Mexico. A significant result indicates that temporal shifts of the measured variable were of the same sign (values increasing or decreasing) in most of the bay systems around the Gulf

Parameter	KS Statistic	P Value
Silver	0.11218	0.3833
Arsenic	0.17949	0.0840
Cadmium	0.11859	0.3744
Copper	0.19551	0.0601
Mercury	0.11859	0.3744
Selenium	0.50321	6.0×10^{-8}
Zinc	0.21795	0.0313
Total PAH	0.05128	1.00
Condition index	0.38782	5.9×10^{-5}
Length	0.34936	3.4×10^{-4}
P. marinus mean infection	0.48718	6.0×10^{-8}
P. marinus mean prevalence	0.21795	0.0313

P. marinus infection intensity all were characterized by nearly Gulf-wide coincident oscillations in yearly values.

Meteorological data (Trenberth et al., 1988; Ropelewski & Halpert, 1986; Douglas & Englehart, 1981) suggest that the eastern and southern Gulf are dissimilar from the western Gulf. Powell et al. (1992) found that *P. marinus* prevalence followed this trend. Consequently, substantial geographic areas of similarity might go unrecognized at a spatial scale encompassing the entire Gulf of Mexico. Accordingly, we also looked at groups of 10 bay systems covering approximately 600 km of coastline (range 500–900 km, excepting those that "wrap around" the Gulf, thereby including the eastern and western portions of the southern Gulf) (Figs 6–8).

Average length of the oysters sampled tended to decrease in each year throughout the study. The largest oysters were always preferentially sampled at each site. The decrease in length could represent the depletion of the largest individuals over time due to this sampling strategy; however, the decrease occurred in fished and unfished populations and, in many areas, most collected oysters were no more than 2 years old. Accordingly, collections the previous year would not have sampled the same cohort. Trends in size, then, are probably a natural phenomenon. Yearly trends in length are coincident over most of the Gulf, except the Galveston Bay/Sabine Lake area of Texas, length increasing or decreasing from one year to the next coincidentally in most bays within a contiguous group of 10 (Figure 8). Of particular note are the highly significant concordancies in the eastern and southern Gulf of Mexico. Yearly trends in length in southern Texas and southern Florida were nearly identical, small oysters being collected in certain years and large oysters in other years.

Low values of condition index typically indicate a stressed or unhealthy population. Condition index also varies with the reproductive cycle. In 1989, 3 of the 26 bay systems had condition indices greater than 0.1, while 1986 had 15, 1987 24 and 1988 21. The two years with lower mean prevalences of *P. marinus* had higher average condition indices, as might be expected. Similar year-to-year variations in condition index occurred

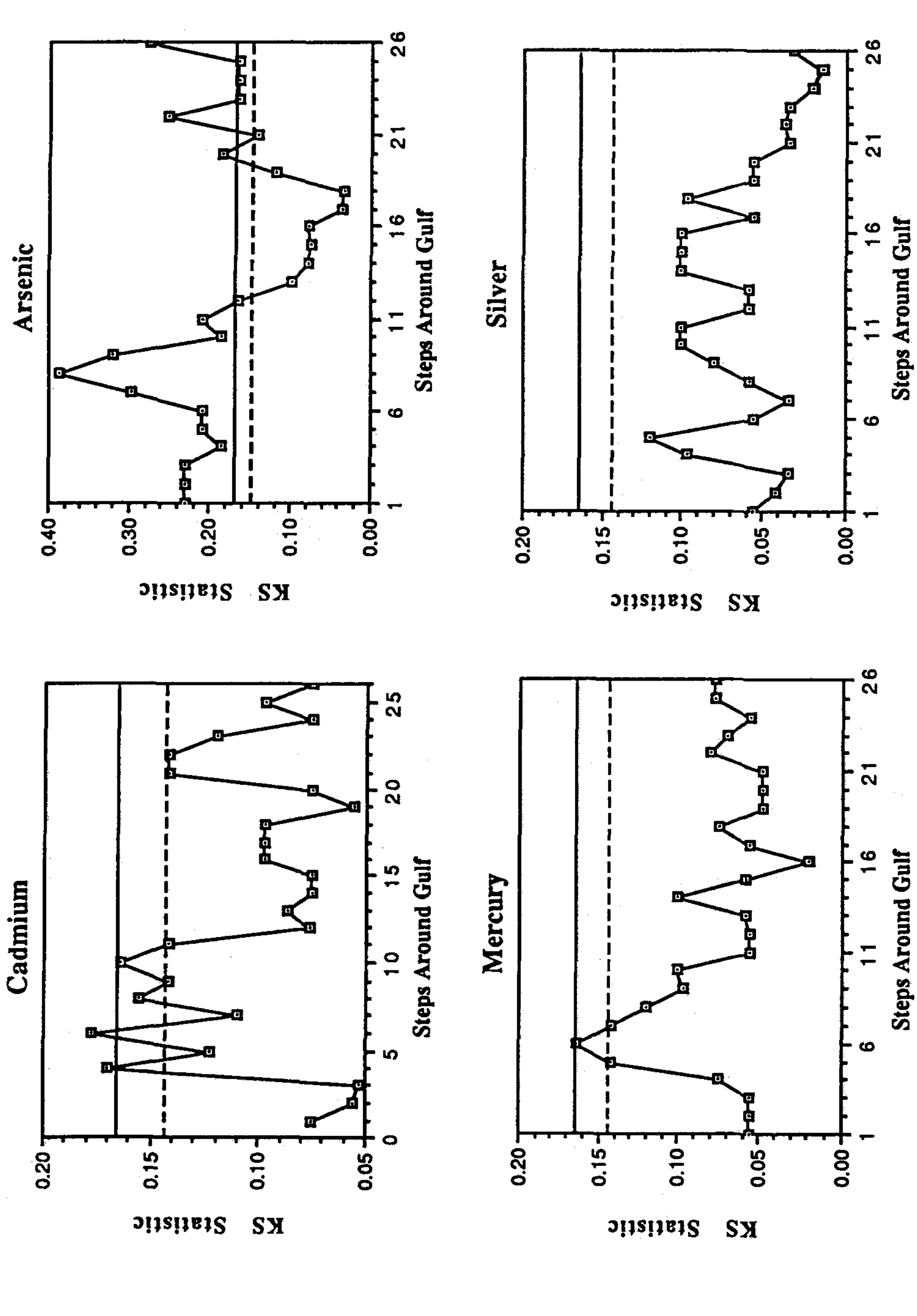


Fig. 6. Graphical representation of results of the Kolmogorov-Smirnov test for arsenic, silver, cadmium, and mercury using all bay pairs in each group of 10 bay systems (one step). The two lines indicate the α = 0.05 (solid) and 0.10 (dashed) significance levels for an n of 45 (number of site pairs used)

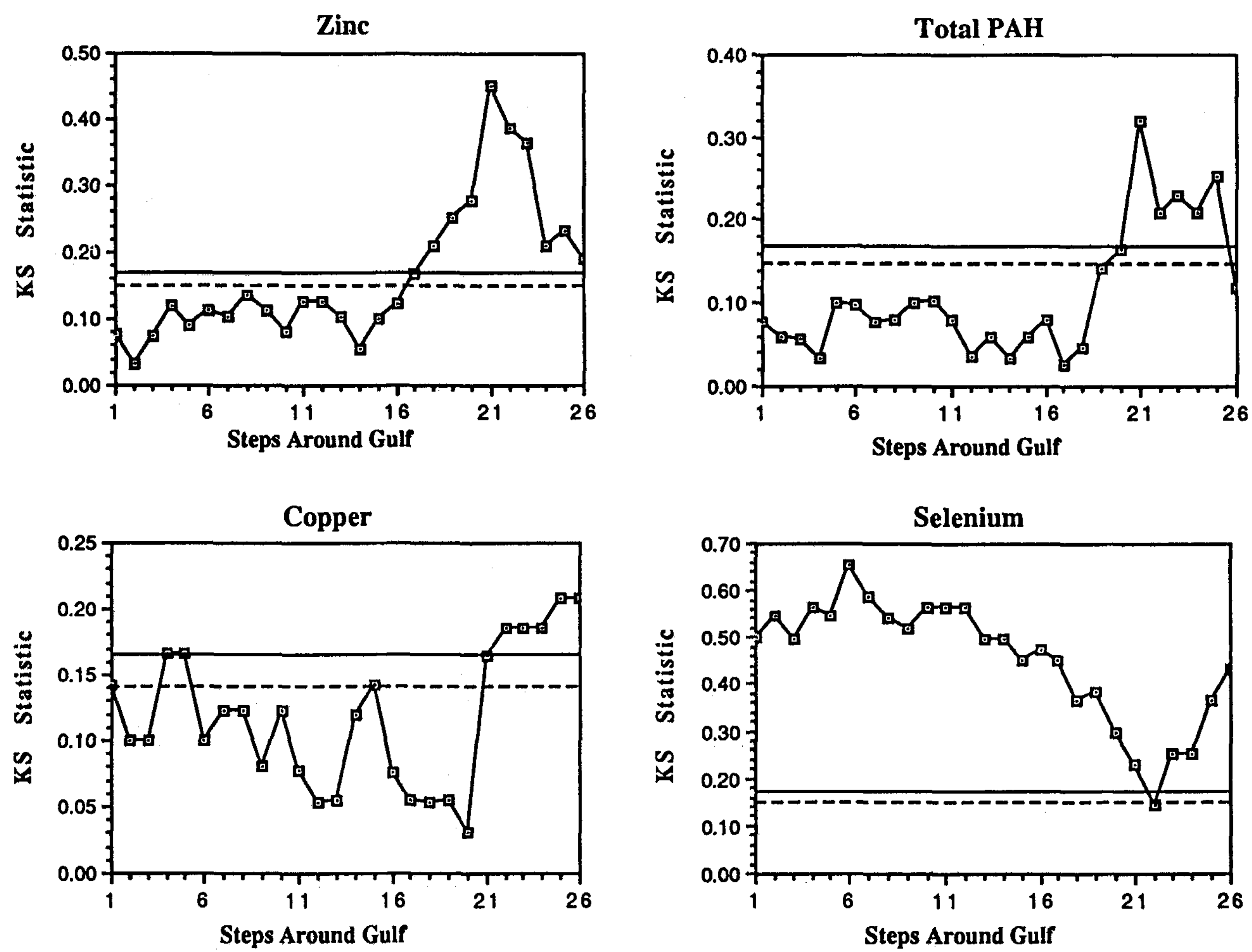


Fig. 7. Graphical representation of results of the Kolmogorov-Smirnov test for selenium, copper, zinc, and PAH using all bay pairs in each group of 10 bay systems (one step). The two lines indicate the $\alpha = 0.05$ (solid) and 0.10 (dashed) significance levels for an n of 45 (number of site pairs used)

throughout the Gulf of Mexico (Figure 8). As the time of sampling of the populations was similar in all cases, except the Louisiana bays in 1986 (Craig et al., 1989; Wilson et al., 1990), this trend indicates that a Gulf-wide variation in climatic conditions probably controls condition index in Gulf oysters.

Similar year-to-year variations in prevalence of *P. marinus* occurred throughout the Gulf with the exception of the central-northern region represented by bays on both sides of the Mississippi River (Figure 8). Powell et al. (1992) noted that the Mississippi River represents an important boundary in *P. marinus* infection. The only uninfected populations in the Gulf of Mexico are regularly found in the Mississippi delta. Concordant year-to-year variations in mean infection intensity of *P. marinus* occurred throughout the Gulf of Mexico, as was the case for condition index and nearly so for length, suggesting a similar relationship with climatic variables, if not a causal process. *P. marinus* infection intensity could be a controlling factor in both length and condition index. Again, in both prevalence and infection intensity, the similarity in yearly trends on both sides of the southern Gulf is noteworthy.

The pollutants divide into 3 groups based on their temporal variations (Figs 6, 7). (1) Like condition index, length and *P. marinus* infection intensity, year-to-year variations in selenium coincided throughout the Gulf. The similarity between selenium and condition index is particularly noteworthy. Year-to-year variations in arsenic were only slightly lower than selenium in their regional scale of concordancy; concordancy occurred over much of the eastern and western Gulf, only failing to encompass the Louisiana region.

(2) Mercury and cadmium varied similarly in the western Gulf, but not in the eastern Gulf. The degree of concordancy was low; large-scale control of body burden occurred only in the Texas region. This pattern, then, is different from all biological parameters.

(3) Year-to-year variations in copper, zinc, and PAH body burden were concordant in the eastern and southern Gulf, particularly Florida and southern Texas, but not in the northern and western Gulf, a trend exactly opposite of that noted for cadmium and mercury. The concordance of yearly variations in body burden on both sides of the southern Gulf is similar to that noted previously for *P. marinus* prevalence and infection intensity and condition index. Again the region of concordancy begins in the Mississippi/Alabama area of the Gulf at a similar location as it does for *P. marinus*, suggesting a similar climatic control.

(4) Silver failed to show regional concordancy anywhere in the Gulf.

DISCUSSION

Explaining the temporal and spatial variation in contaminant body burdens is complicated because body burden may be affected by so many environmental and biological factors (Farrington et al., 1983). Oysters can incorporate metal and organic contaminants either through direct absorption from water or ingestion with food particles (Ehrhardt, 1972; Stegeman & Teal, 1973). Therefore, any factor which affects the bioavailability of pollutants such as changes in environmental condition, physiological condition or food supply may ultimately affect contaminant body burden (Farrington et al., 1983). Factors controlling these conditions are, in the extreme, of two kinds: local and large-scale. These, in the extreme, offer two opposing expectations. In the local case, temporal variations in body burden should never occur simultaneously in adjacent bays

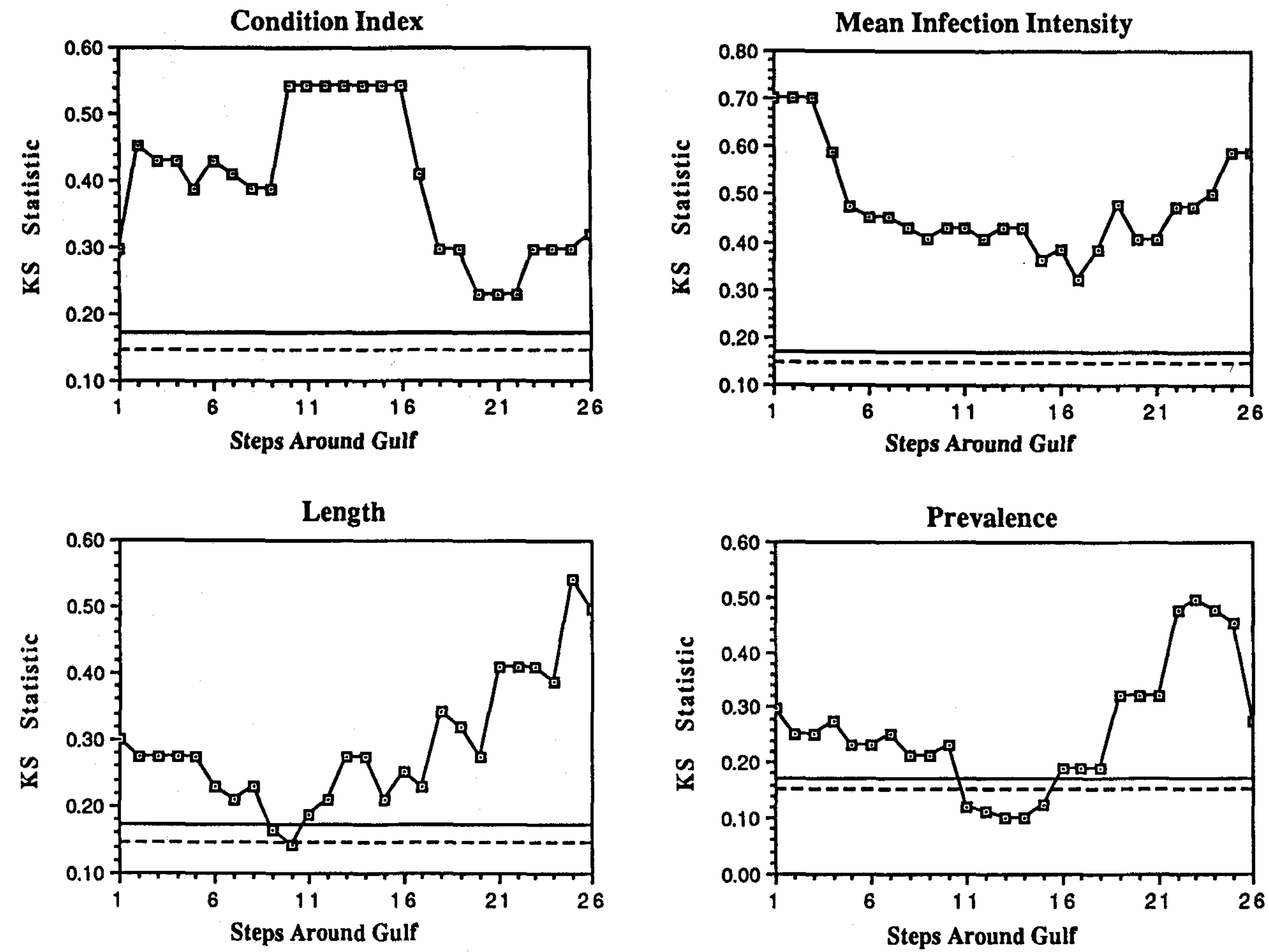


Fig. 8. Graphical representation of results of the Kolmogorov-Smirnov test for condition index, length and the mean infection intensity and prevalence of infection of *Perkinsus marinus* for all pairs in each group of 10 bay systems (one step). The two lines indicate the $\alpha = 0.05$ (solid) and 0.10 (dashed) significance levels for an n of 45 (number of site pairs used)

more frequently than expected by chance. In the large-scale case, we should expect coincidental variations within some large geographic region. It may be true that local variations outweigh large-scale factors in some regions and not in others, depending upon the strength of the two signals. El Niño, for example, affects the southern and eastern Gulf. A contaminant significantly affected by environmental conditions associated with El Niño might show coincidental changes in the eastern and southern Gulf while local variables controlled its temporal variability in the northwestern Gulf. Understanding the variation in contaminant body burden, then, requires investigating the effects of biological and environmental factors on both the local and larger geographic scales.

Temporal distribution and climatic control on variability

The biological attributes and contaminants can be placed into three groups based on the regional scale of their concordant temporal changes in the Gulf. For selenium and arsenic body burden, condition index, length, and prevalence and mean infection intensity of *Perkinsus marinus*, year-to-year variations are similar in nearly every bay around the Gulf. This implies controlling factors Gulf-wide or nearly Gulf-wide in scope. The geographic scale is largest for selenium, *P. marinus* infection intensity, condition index and length, but encompasses all save the Louisiana bays for arsenic and *P. marinus* prevalence. The second group, including mercury and cadmium, varies concordantly from southern Texas to approximately the Mississippi delta, suggestive of some large-scale phenomenon in the northwestern Gulf producing similar changes in body burden for these contaminants. The last group, including copper, zinc, and total PAHs, varies concordantly in southern Texas and southern Florida, suggesting a subtropical control on body burden for these contaminants.

Of particular note are the geographic boundaries of these three groups. The boundaries between the northwestern and the southern/eastern Gulf are clear; the vicinity of the Mississippi River delta and the Matagorda/Aransas Bay area of Texas. The break in similarity for arsenic and *P. marinus* prevalence in the Mississippi River region also marks the eastern extent of similarity for mercury and cadmium and the western extent for copper, zinc and PAHs. The western extent of similarity for mercury and cadmium, Matagorda Bay, approximates the northern extent of similarity for PAHs, zinc and copper.

These groupings of contaminants and biological attributes require three levels of explanation. First, if only climatic factors are of sufficient scale to explain the concordances observed, what climatic factors are ultimately responsible? Second, why are certain groups of pollutants climatically controlled only in one part of the Gulf; do geochemical similarities, for example, explain these groupings? Third, what factors mediate the climatic control on body burden?

Climatic controls. Large-scale concordances in temporal change can only be explained by climatic factors; only these operate on an appropriate geographic scale. Choices for the climatic factors ultimately responsible are relatively limited. (Of course, our data do not permit us to verify what the ultimate causative factors are. A 4-year time series is inadequate for statistical treatment.) The concordant shifts in the eastern and southern Gulf suggest a tropical or subtropical control. The El Niño/Southern Oscillation phenomenon is of appropriate scale and location. El Niño occurs in the Pacific, but affects temperature and rainfall in the Gulf of Mexico region by altering dominant weather patterns (Trenberth et al., 1988; Philander, 1989) and has been implicated in temporal variations in *P. marinus* prevalence and infection intensity. El Niño/La Niña events typically affect the Gulf from the panhandle of Florida through southern Florida and southern Texas, where concordancy for selenium, arsenic, copper, zinc, PAHs and most biological variables occur. A strong El Niño/La Niña shift occurred between 1987 and 1988 and contributed to the North American drought that summer (Philander, 1989). We noted that the year groups 1986/87 and 1988/89 tended to be statistically similar in many analyses, as did Powell et al. (1992). A second large-scale meteorological phenomenon, the Pacific North American Teleconnection (PAMT), controls the number and severity of winter storms in the northwest Gulf region (Wallace & Gutzler, 1981) where concordancy for mercury and cadmium, as well as selenium, arsenic, and most biological variables occurs. Combined, these two weather patterns could explain the geographic scale of concordancy observed in each of the contaminants and biological variables.

Why groupings exist. Any of the contaminants or biological attributes might respond to two scales of environmental change. Local changes, originating for example from the nearness of urbanized areas, the presence of certain contaminants in particular drainage basins and the extent of agricultural development, should produce discordance between adjacent bay systems. Galveston Bay, for example, might drain a large geographic area whereas an adjacent bay, East Matagorda Bay, may receive only local precipitation. Contrasting with this are large-scale climatic trends which affect weather patterns at least regionally. Changes in the precipitation regime during El Niño cycles are a good example. All watersheds in regional areas may be affected in the same way. Depending upon the competing strengths of local and climatic variability, biological attributes or contaminants might respond most strongly to one or the other. In our case, the body burdens of copper, zinc and PAHs would appear to be predominantly under local control in the northwestern Gulf and under climatic control in the eastern/southern Gulf. Mercury and cadmium have the opposite distinction. Selenium, arsenic and many of the biological attributes respond regionally in both areas. Silver seems generally to be under local control.

For the first two groups, the reason why local controls are relatively more important in one region than another is unclear, nor is it clear why cadmium and mercury behave similarly, as do copper, zinc and PAHs. To the extent that copper and zinc often behave similarly in bivalves (Phillips, 1976a, b; Phelps et al., 1985; Roesijadi & Klerks, 1989) and quite differently from cadmium (Brooks & Rumbsy, 1965; Boyden, 1974; Cheng, 1988a, b; but see Roesijadi et al., 1989), these data fit an expected scenario.

Mediating factors. We used R^2-improvement and regression analyses on the yearly rankings for those locations in the Gulf demonstrating concordant yearly shifts to examine what biological and climatic parameters might contribute most to the observed concordancy. Inasmuch as the biological parameters certainly were also influenced by climatic parameters, the set of independent variables were not in themselves completely independent; thus the analyses serve as a guide to the mediating factors responsible only in this context. Moreover, we expected factors to differ between the northwestern and the eastern and southern Gulf regions.

In determining which variables might affect *P. marinus*, we considered condition index, monthly mean temperature, monthly mean precipitation, length, cadmium, selenium, zinc, copper, PAHs, silver and mercury (Table 7). *P. marinus* prevalence was positively correlated with mercury body burden and negatively correlated with temperature and condition index in the western Gulf. Negative correlations existed for zinc, selenium, copper and cadmium and positive correlations for PAHs and arsenic in the eastern and southern Gulf (Table 7). *P. marinus* infection intensity responded negatively to selenium, condition index, and length and positively to copper in the western Gulf; condition index and selenium demonstrated negative correlations in the eastern and southern Gulf. These correlations demonstrate several important trends. (1) Biological variables were the most important correlates of the distribution of *P. marinus* in the western Gulf where concordance in contaminant body burden was least well developed; contaminants were most important in the eastern and southern Gulf where the El Niño signal was strongest. (2) Most correlations were negative for biological and environmental variables and contaminants. Mercury, copper and PAHs were important exceptions. (3) The negative relationships with condition index and length are, perhaps, expected; that with temperature is a surprise as is the absence of an effect of precipitation. (4) The most consistent Gulf-wide signals were negative correlations with selenium body burden and condition index. Both of these responded concordantly throughout the Gulf as did *P. marinus* prevalence and infection intensity.

The parameters used for the analyses of the contaminants were length, condition index, *P. marinus* prevalence and mean infection intensity, and mean monthly temperature and mean monthly precipitation for the two months prior to sampling. Cadmium, mercury and arsenic varied concordantly in the northwestern Gulf (Table 8). Tempera-

Table 7. Results of regression analyses within regions of concordancy of yearly changes for *Perkinsus marinus* prevalence and infection intensity. Possible significant results represent the number of steps or groups of 10 bay systems tested individually. Number given indicates the number out of that possible number significant at $\alpha = 0.10$. N, a negative correlation; P, a positive correlation

P. marinus prevalence			
Western Gulf		Eastern/southern Gulf	
(10 possible)		(11 possible)	
Temperature	9 N	Arsenic	6 N
Condition index	9 N	Copper	4 P
Mercury	7 P	Cadmium	5 N
		PAH	4 P
		Zinc	6 N
		Selenium	8 N
***P. marinus* infection intensity**			
Western Gulf		Eastern/southern Gulf	
(15 possible)		(10 possible)	
Copper	7 P	Condition index	10 N
Length	12 N	Selenium	5 N
Condition index	15 N		
Selenium	8 N		

Table 8. Results of regression analyses within regions of concordancy of yearly changes in contaminant body burden. Possible significant results represent the number of steps or groups of 10 bay systems tested individually. Number given indicates the number out of that possible number significant at $\alpha = 0.10$. N, a negative correlation; P, a positive correlation

Arsenic (Western Gulf) (8 possible)		**Arsenic** (Eastern/southern Gulf) (7 possible)	
Temperature	6 N	Precipitation	4 N
Condition index	5 P	Temperature	3 N
Mercury (Western Gulf) (3 possible)		**PAH** (Eastern/southern Gulf) (6 possible)	
Temperature	3 P	Temperature	3 N
Precipitation	3 P	Length	3 N
Cadmium (Western Gulf) (9 possible)		**Copper** (Eastern/southern Gulf) (6 possible)	
Perkinsus marinus intensity	4 N	*Perkinsus marinus* prevalence	3 N
Length	3 N	Length	6 N
		Condition index	2 N
Selenium (Entire Gulf) (26 possible)		**Zinc** (Eastern/southern Gulf) (10 possible)	
Length	24 N	*Perkinsus marinus* prevalance	8 N
Condition index	15 N	Temperature	6 N
Temperature (only southern sites)	7 N	*Perkinsus marinus* intensity	6 P
Precipitation (only northern sites)	11 N		

ture (negative), length and condition index (positive) generally explained about 35 % of the variation for arsenic; temperature, length (negative) and mean infection intensity (positive) explained 25–35 % of the variation for cadmium. Mercury responded positively with temperature and *P. marinus* prevalence.

Copper, zinc, arsenic and PAHs generally varied concordantly in the eastern and southern Gulf. Temperature (negative), mean infection intensity (positive) and prevalence (negative) explained 30 to 50 % of the yearly variation in zinc. Prevalence (negative), condition index (negative) and length (negative) explained 35 to 55 % of the variation in copper. For PAHs, temperature (negative) and length (negative) were most important. Temperature and precipitation were most important for arsenic.

Selenium body burden varied concordantly over most of the Gulf. In the northwestern Gulf, precipitation (negative), length (negative) and condition index (negative) explained 35 to 75 % of the variation. In the eastern and southern Gulf, condition index (negative), length (negative) and temperature (negative) explained 25 to 45 % of the variation.

Overall, then, a few trends were evident. (1) Regressions with condition index and length were generally negative; higher body burdens occurred in smaller oysters, which is a general phenomenon (Boyden, 1977; and others referenced previously). Lower condition index suggests that small size was not just indicative of young oysters, but in fact indicates oysters in poorer health (less biomass per length or mantle cavity volume). The relationship between *P. marinus* infection intensity and condition index corroborates this view. (2) Temperature was usually negatively correlated. The exception was mercury, where temperature was a positive factor. Although temperature might directly affect body burden, we would suggest that temperature probably controls the frequency of fall spawning and spawning generally results in lower pollutant body burdens (e.g. Frazier, 1975, 1976; Boyden & Phillips, 1981; Wilson et al., 1990), hence the higher body burdens at lower temperatures. (3) Precipitation was generally negatively correlated, suggesting higher salinities corresponded to higher body burdens, but precipitation was only important in selenium and arsenic. For the most part, temperature and precipitation were not themselves correlated, the exception being the north-central Gulf. (4) Arsenic is taken up primarily from food (Sanders, 1980; Sanders et al., 1989); accordingly, it is likely that the response of body burden to climatic factors was biologically mediated in at least this case. (5) *P. marinus* prevalence and mean infection intensity were important in copper, zinc, mercury and cadmium. Correlations were generally negative with prevalence but positive with infection intensity. Again, mercury was the exception. Lower prevalence would correspond with lower temperatures (Soniat & Gauthier, 1989). Prevalence includes many light infections which probably are meaningless with respect to body burden. High infection intensities, on the other hand, probably slow reproduction (White et al., 1988; Wilson et al., 1988; Wilson et al., 1990) and are likely responsible for the observed reductions in condition index and length.

Again, we emphasize the intimate relationship between *P. marinus* and the other biological and environmental variables; consequently, the analyses can only provide a rough estimate of the relative importance of these variables without the actual processes being more completely understood. Overall, the factors affecting the rate of tissue turnover, particularly the gametogenic cycle and general health, determined in part by the temperature regime and disease intensity, would seem to be of primary importance in determining yearly trends in contaminant body burden (see also Wilson et al., 1990). Generally, higher contaminant body burdens were found in populations characterized by lower health.

Spatial distribution and climatic control on variability

Gulf-wide trends. As with *P. marinus*, most characteristics of the spatial distribution of the pollutants were conservative features; they were repeated in each of the 4 years. A general clinal relationship might be expected to dominate the spatial distribution of contaminants; bays farther and farther apart being less and less similar in body burden. Temperature and precipitation show this clinal relationship (Fig. 9). The farther sites are apart, the less similar the local weather regimes are likely to be. Many geographical variables related to contaminant source availability probably do so as well. River inflow does not (Fig. 9).

Arsenic, selenium, mercury and cadmium show gradually declining similarities with distance; the clinal variation predicted from the precipitation and temperature regime. The correlograms of copper, zinc, silver and PAHs do not; the spatial extent of regional similarity is of varying size throughout the Gulf so that no consistently significant spatial

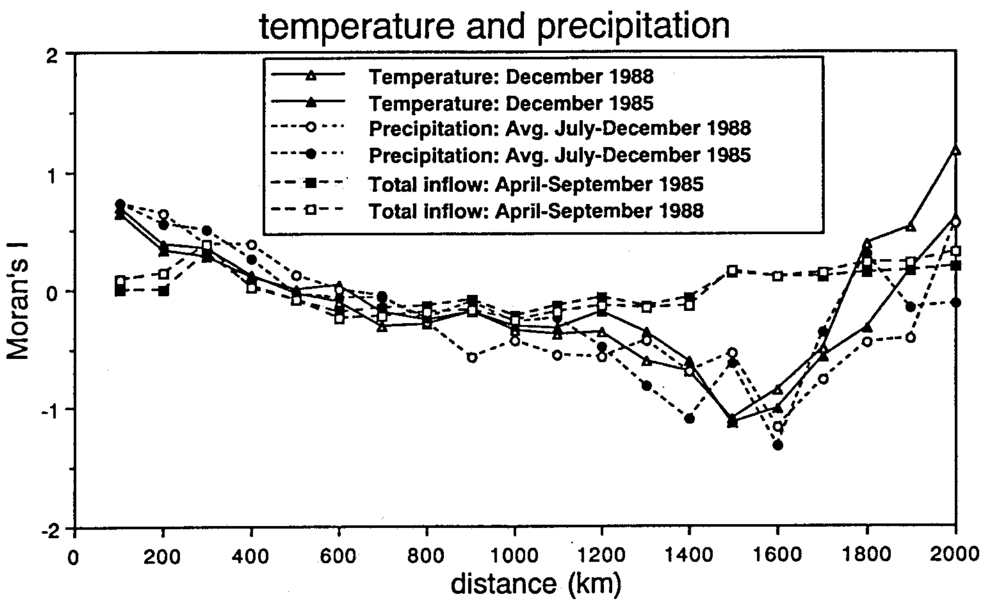


Fig. 9. Correlograms relating distance (km) to Moran's I obtained using temperature, precipitation and total freshwater inflow for all sites sampled in each year. Distances were calculated along the Gabriel network, where stations separated by, for example, 101 and 200 km were used to generate the 200-km point. See Powell et al. (1992) for more details

scale exists. Why these two groups differ can be related to the temporal trends previously described. From one year to the next, the body burden of selenium and arsenic varied concordantly throughout the Gulf; the body burden of cadmium and mercury was predominately affected by local factors throughout the Gulf. In both cases, the Gulf-wide trends were sufficiently uniform that local factors of a clinal nature might successfully generate a strong spatial signal throughout the Gulf in any given year. In contrast, for those contaminants having a strong regional response in the year-to-year variability in the eastern Gulf, but which were locally-controlled in the western Gulf (copper, zinc and PAHs), fundamental differences in the controlling factors between the two regions probably prevented a general clinal relationship from being observed throughout the entire Gulf.

None of the correlograms mimic those of local agricultural or urban land use (Craig et al., 1989) or *P. marinus* prevalence and infection intensity (Powell et al., 1992). It is tempting, therefore, to suggest that the precipitation and temperature regimes are important in controlling site-to-site trends in contaminant body burden over large geographic areas, whereas organism health modifies these bay-to-bay relationships on smaller regional scales. A correlation with latitude and the body burden of some contaminants does exist in Gulf coast oysters (Wilson et al., 1990). Temperature and freshwater inflow can change the supply of contaminants and therefore their bioavailability (Shuster & Pringle, 1969; Zaroogian & Cheer, 1976; Denton & Burdon-Jones, 1981). Cunningham & Tripp (1973, 1975b), Zaroogian & Cheer (1976), Zaroogian (1980), and

Zaroogian & Hoffman (1982), for example, comment on the temperature dependence of body burdens in cadmium, mercury and arsenic either linked directly to temperature or a seasonal biological cycle, such as reproduction, that correlates directly with temperature (Wilson et al., 1990). Parizek et al. (1974) describes a relationship between selenium, cadmium and mercury. Several sources cite the co-occurrence of zinc, copper and silver, and that a common source for these metals is freshwater runoff (Windom & Smith, 1972; Frazier, 1975; Phillips, 1977b, c), as is also likely for PAHs (Wade et al., 1988). Body burdens of copper and zinc may also be related to salinity (Wright & Zamuda, 1987). Nevertheless, sufficient data is not now available to identify the primary controlling factors behind the large-scale distribution of contaminants in the Gulf.

Regional correlations. We examined the correlations between various environmental and biological variables and contaminant body burdens within the regions observed to have concordant yearly shifts in body burden; the reason being the expectation that the significant variables controlling body burden may be different in different areas of the Gulf and that the areas providing concordant temporal trends might offer some guidance in dividing the Gulf into regional areas.

Using the 5-month average for precipitation and temperature (no measures of *P. marinus* infection included) (Table 9) shows that precipitation and temperature are only significantly correlated with some contaminants and are only significant in 1986 and 1988. Whereas precipitation is always positively correlated, temperature is negatively correlated, indicating that high precipitation and low temperatures over long periods of time before sampling may influence body burden. Agricultural and industrial land use are also important for some contaminants. Including *P. marinus*, and necessarily using a shorter time scale (2 months) (Table 10), shows that *P. marinus* prevalence and mean infection intensity are often significantly correlated with contaminant body burdens within regions showing similar temporal responses to climatic variation.

Despite the seeming likelihood that large-scale trends in the Gulf must ultimately originate in Gulf-wide trends in temperature and freshwater inflow, few of the contaminants show consistent correlations with either temperature or precipitation on the regional level, and these regions typically cover a substantial range in latitudes (Tables 9, 10). In fact, from these analyses, local input from industrial and agricultural land use and levels of *P. marinus* infection appear to be more important. Most pollutants show a significant correlation with some measure of *P. marinus* infection in at least one instance. The relationship between *P. marinus* and temperature and salinity (again, related to precipitation) is well documented in the literature (Mackin, 1962; Soniat, 1985; Soniat & Gauthier, 1989). Correlations are more frequent using the average of the climatic data for the 2 months before sampling rather than for the 5 months before sampling, suggesting that response times to variations in environmental variables might be more nearly 2 than 5 months, and this is the response time expected if *P. marinus* was an important factor in body burden (Choi et al., 1989). The infrequent correlations with length, condition index or *P. marinus* prevalence (as opposed to infection intensity) are also noteworthy, particularly considering the frequent importance of these biological indices generally (Cossa et al., 1980; Scott & Lawrence, 1982; Lytle & Lytle, 1990; Páez-Osuna & Marmolejo-Rivas, 1990; and others referenced previously) and in the temporal trends we observed. Recall, however, that *P. marinus* infection intensity, condition index and length are correlated on most spatial scales.

Table 9. Results of regression analyses within regions of similarity in pollutant body burden as determined using the K-S test. These results use the average of the 5 months prior to sampling for precipitation and temperature. * signifies a significant negative correlation. CI = Condition index; Industry refers to industrial land use; Agriculture refers to agricultural land use

Pollutant	1986	1987	1988	1989
Arsenic	----	----	Length P = 0.0099*	----
Cadmium	Precipitation P = 0.0457 Temperature P = 0.0167*	Industry P = 0.0473	Length P = 0.0057	----
Copper	----	----	----	----
Mercury	Industry P = 0.0441*	----	Industry P = 0.0150*	Industry P = 0.0274* Agriculture P = 0.0446
Selenium	Agriculture P = 0.0054	----	Agriculture P = 0.0021	Agriculture P = 0.0416
Silver	----	----	----	----
Zinc	Precipitation P = 0.0074 CI P = 0.0035	----	Precipitation P = 0.0145	----
PAH	----	----	----	----

Table 10. Results of regression analyses within regions of similarity in pollutant body burden as determined using the K-S test. These results utilize the average of the 2 months prior to sampling for precipitation and temperature. Mean and Median Infection and Prevalence refer to *Perkinsus marinus*. Other abbreviations and symbols as described in Table 9

Pollutant	1986	1987	1988	1989
Arsenic	Industry P = 0.0002* Prevalence P = 0.0472	Precipitation P = 0.0111*	Length P = 0.0061*	Precipitation P = 0.0183* CI P = 0.0098 Median Infection P = 0.0135*
Cadmium	CI P = 0.0162* Prevalence P = 0.0310 Mean Infection P = 0.0044*	Industry P = 0.0483	Precipitation P = 0.0087* Length P = 0.0037 Mean Infection P = 0.0132*	- - - -
Copper	Temperature P = 0.0366	Mean Infection P = 0.0062 Median Infection P = 0.0053*	Temperature P = 0.0230	Industry P = 0.0402* Median Infection P = 0.0290 Prevalence P = 0.0308*
Mercury	Industry P = 0.0416* Prevalence P = 0.0116	Industry P = 0.0199* Mean Infection P = 0.0187	- - - -	Temperature P = 0.0383* Agriculture P = 0.0187 Industry P = 0.0204*
Selenium	Agriculture P = 0.0023 Mean Infection P = 0.0159*	Agriculture P = 0.0285 Mean Infection P = 0.0159 Median Infection P = 0.0173*	Agriculture P = 0.0037	Agriculture P = 0.0264
Silver	Precipitation P = 0.0082* Prevalence P = 0.0429 Mean Infection P = 0.0042* Median Infection P = 0.0177	- - - -	- - - -	Length P = 0.0168 CI P = 0.0073 Prevalence P = 0.0006* Median Infection P = 0.0010
Zinc	Precipitation P = 0.0082 CI P = 0.0039*	- - - -	Median Infection P = 0.0267*	Length P = 0.0257
PAH	- - - -	- - - -	Prevalence P = 0.0247 Mean Infection P = 0.0241*	Length P = 0.0101

Whether a cause and effect relationship exists between disease and contaminant body burden has not been demonstrated. *P. marinus* can produce physiologic abnormalities in its oyster host that in turn can affect the oyster's ability to feed (Mackin & Ray, 1955). Since feeding is one method of uptake for certain contaminants, such as arsenic (Sanders et al., 1989), body burden could be reduced with increased infection of *P. marinus.* Contaminant exposure and disease may also affect the health of the digestive gland (Bayne et al., 1979; Axiak et al., 1988). Cadmium has been shown to stimulate phagocytosis (Cheng, 1988a) which is one means of defense against disease (Fisher & Newell, 1986; Fisher & Tamplin, 1988). The negative correlation between cadmium body burden and *P. marinus* may be a reflection of this stimulatory action.

CONCLUSIONS

The results of environmental monitoring studies have long been looked upon with suspicion when the results have been compared over varied environmental conditions (Phillips, 1977a). Our results stress the variability of pollutant body burdens as they relate to variations in environmental and physiological conditions. Consideration of local controls are important, but so are large-scale geographic and climatic controls which can override the local controls. All biological variables responded regionally on a Gulf-wide scale. Local controls were relatively unimportant throughout the Gulf in explaining temporal trends, albeit of more importance in explaining the spatial relationships within any one year. Among the contaminants, local and regional controls were important in discrete geographic areas in most cases. Some contaminants responded primarily regionally (e.g. selenium), some primarily locally (e.g. silver). These regional differences affected not only the temporal trends, but also the spatial distribution of body burden within any one year. Accordingly, consideration of the spatial distribution of body burden, and particularly, consideration of the temporal trends in body burden must take into account that climatic factors may be more important in some regions than others and that the health of the population may contribute markedly to body burden; consequently, factors controlling the health of populations may indirectly affect temporal trends by mediating the climatic response.

Variations in source content have not been included in the analysis. Inasmuch as arguably the most important parameter controlling body burden has not explicitly been included in the analysis, the fact that several environmental and biological parameters nevertheless demonstrated significant correlations with body burden is noteworthy. Among the biological parameters, factors related to disease, and among the environmental parameters, factors related to land use and meteorological conditions are likely to play an important role in determining pollutant body burden at least regionally. It is particularly important to recognize that regional factors of importance may go unrecognized at larger geographic scales because statistical analyses may be compromised by varying responses to selected variables in different regions. We should not expect selected variables to be consistently of paramount importance everywhere.

Both *P. marinus* prevalence and intensity, as well as the other biological variables, and contaminant body burdens must ultimately respond to temperature and rainfall. These latter two parameters should be the initial factors mediating the effect of climate on pollutant body burden. Whether they are the proximate causes, or whether biological parameters intercede, remains unclear. Certainly, however, factors like disease intensity and the gametogenic cycle play an important role in determining the health and condition of Gulf oyster populations. That the contaminant body burdens in the Gulf are almost uniformly relatively low suggests that the correlations observed between body burden and biology originate either in biological control of contaminant body burden or coincident control of both directly by climatic cycles rather than the impact of pollution on organism health (e.g. Khan, 1990) which might result at higher exposure levels.

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