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THE LARVAE DYNAMICS OF *CANCER MAGISTER*
IN THE COOS BAY ESTUARY

Master's Thesis
by David Rowell

Thesis never submitted.

INTRODUCTION

The role of an estuary or bay in the life cycle of *Cancer magister* is not well understood. I believe Coos Bay, as well as other bays, is an important "nursery" ground for young crabs, its recruits are necessary for sustaining a commercial fishery. Tasto(1978) has shown that juveniles account for a larger percentage of an estuary's crab population than in nearshore waters. The juveniles in the S.F. Bay-complex exhibited a growth rate nearly twice that of ocean-reared crabs (Tasto et al 1981). It is postulated that this is due to reduced predation pressure and increased food supply within the estuary.

During the late spring and early summer the late larval and early juvenile stages of *C. magister* migrate onshore, enabling them to remain in favorable habitats on the continential shelf, in bays and estuaries. This onshore movement during the last larval stage, megalopa, is accentuated by a particular set of oceanographic conditions. The purpose of the analysis is to compare two years of bay zooplankton samples in an attempt to better understand these oceanographic conditions by which this onshore transport is facilitated. Sample abundance in the bay is assumed to indicate general trends in relative bay abundance. The distribution and timing of the larval phases is interpreted from sample abundance. This information is then correlated with oceanographic parameters in an attempt to explain conditions creating annual and diurnal fluctuations of *C. magister* larvae in the Coos Bay estuary. In addition, behavior of megalopa was examined in the laboratory to aid in understanding mechanisms involved in larvae transport and settlement.

Cyclic patterns in crab catch have been observed along the entire west coast since the 1930's (Figure 1). These fluctuations are caused by an interplay between the biology of the organisms (i.e. age structure) and enviromental conditions (Bakun 1971). Lough (1975) proposed that survivorship during the larval period [illegible]

[illegible]

was the critical factor in determining adult year-class strength. The reproductive strategy of *C. magister* corresponds to major features in surface water transport. Their pelagic larvae occur during the winter and spring when the general surface wind drift is onshore and not during the more productive upwelling season. My hypothesis is that onshore-offshore larval transport is this key factor involved in survivorship and subsequent recruitment. I will explore this as a possible explaination to the fluctuating crab year-class strength by utilizing Bakun's (1973) Upwelling Indices as an indicator of inter-year differences of surface drift conditions and the the resultant onshore-offshore larvae transport. Only the upwelling conditions during the megalopa stage will be utilized in this analysis because the late zoeal stages are located below 5m depth where wind-induced transport is minimized (Lough 1976). Then I discuss the feasiblity of previously proposed explainations to these cyclic fluctuations in the crab catch.

Considering that approxiametly 99% of all mortality occurs in the larval stage, the importance of meroplankton research can not be overemphasized. Knowledge of larval dynamics is imperative for proper implementation of fisheries management. With this in mind , I will present recommendations for further research deemed necessary for clarification of certain aspects associated with predicting *C. magister* recruitment levels. Anticipating annual recruitment levels will help dictate the fishing strategy that would maximize and stabilize long term yields from standing stocks.

OCEANOGRAPHIC FEATURES

The pelagic larval stage can result in dispersal of offspring to habitats "potentially" great distances from their hatching site. Any larvae's latitudinal dispersal and onshore-offshore transprt is highly dependent on the net flow of surface wind drift and the underlying geostrophic current field (Bakun and Nelson 1977).

Surface wind drift known as Ekman transport is calculated as a ratio of wind stress and the local Coriolis value (Sverdrop 1942). Ekman drift occurs in the upper 20 to 30m of water, but decreases exponentially with depth due to frictional resistance. The onshore-offshore component of surface water flow is mainly dependent on this large-scale Ekman transport. When the surface wind drift is directed offshore diverence occurs next to the coast. Divergence is the net loss of surface water and and upward pumping of deeper waters, known as coastal upwelling. Coastal convergence resulting from onshore surface drift leads to downward intrusion of surface water. This phenomena transports surface plankton onshore, it is commonly referred to as downwelling.

The nearshore geostrophic flow runs parallel to the coast at approxiamtely 60m depth. Patterns of geostrophic flow are constructed from temperature and salinity values. Latitudinal displacement of larvae is largely dependent on the annual mean geostrophic flow. Along the U.S. West Coast geostrophic flow is generally dominated by the California Current, a continuation of the Aluetian Current of the North Pacific. This is a characteristically slow, broad and shallow current flowing southeast (Sverdrop 1942). It has a maximum width of 300 miles and a relatively slow velocity of .2 knots (Lough 1971, Sverdrop 1942).

For the purposes of this report I will concentrate on the seasonal oceanographic transport mechanisms in the Pacific Northwest, Cape Blanco to Vancover Isand. In comparison to the remainder of the west coast of the U.S. this region has a relatively weak mean geostrophic flow and offshore Ekman transport. (Parrish 1977).

During the spring and early summer, Mar.-Aug., north-northwest winds prevail off the coast of Oregon and the California Current, flowing southward between latitudes 48° and 23° N, dominates latitudinal surface transport. Offshore transport of surface water characterizes this period. Coastal sea surface temperatures fluctuate radically due to an interplay of increased solar radiation and the pulsing strength of upwelling.

In the late summer, Sept.-Oct., the northwest winds slacken and the upwelling pattern breaks down into irregular eddies. Colder coastal waters shink while warm waters of the pelagic zone move onshore.

During the winter months, Nov.-Feb., the California Current weakens due to winter conditions in the Artic Basin and winds are predominantly from the southwest. The California Current dissappears from the surface layer to be replaced by th northward flowing Davidson countercurrent. The Davidson Current runs slightly closer to the coastline, within 20 miles, reaching maximum speeds of 2 knots (Wyatt et al 1972). Due to intermittent storm patterns, onshore-directed wind-driven transport events are interspersed with relatively weak offshore transport episodes. However, the net large-scale movement of surface water is northward and onshore. The nearshore waters during this Davidson Period are characterized by moderate sea surface temperatures and lower overall carbon production. In the Pacific Northwest inter-year differences exist in the seasonal onset, intensity, and duration of surface transport conditions previously described.

The movement of surface water within 5 miles of the coast is highly dependent on semi-diurnal tidal currents. In summary, the net onshore-offshore and latitudinal movement of nearshore surface waters is an integration of seasonally dominant geostrophic currents, Ekman transport, semi-diurnal tidal currents and localized coastal topography generating irregular eddy formation.

In estuaries and bays the tidal influence on surface water movement is magnified. Tidal prisms, in many cases, account for a large percentage of the total water volume. In addition, the ebbing of surface currents in estuaries is accelerated by freshwater runoff.

LIFE CYCLE

Cancer magister, otherwise known as the Dungeness or edible crab ranges in distribution long the Pacific Coast of North America from Unalaska, Alaska to Magdalena Bay, Baja California (Schmitt 1921). It is a commercially important fishery between Monterey, California and Vancover, British Columbia.

Off the coast of Oregon the Dungeness crab reaches sexual maturity after three years. Butler (1960) concluded that males are polygamous. This important in fisheries management since only males can be harvested. A large percentage of Cancer magister's mating takes place at the perimeter of tideflats in association with algae and eelgrass (Mckay 1937, Spencer1932, personal observation). Breeding pairs have been observed in Coos Bay during April and May (Figure 2). The timing of copulation is closely linked to the female's molting cycle. Premating and mating behavior has been described by Snow and Neilsen (1966). Transfer of sperm via the gonophore into the spermathecae can only take place after the female has molted and before the new shell has hardeded. The spermatophores remain viable within the spermatheca until the ova mature (Mckay 1942, Butler 1960). Wild et al (1978) concluded that the sperm recieved during one breeding season can remain viable to fertilize a second clutch of eggs the following season. Several months after the mating season, the sperm having remained in receptacles of the spermatheca can now fertilize the eggs leaving the oviducts. The number of eggs carried by an individual female is related to her size, food supply, and ambient temperature (Wild et al 1981). Egg deterioration and mortalities are associated with elevated ambient temperatures, pollutants, egg predation and cannabalism (Wickham 1977, Wild et al 1981). When first deposited the eggs are a bright orange but progressively darken as the yolk is consumed. Just prior to hatching the eggs become a gelatinious dark red. The females have been known to remain ovigerious as long as six months.

Spawning into free-swimming larvae occurs nearshore in late December and January and to a lesser degree larvae releases occur intermittenly throughout winter and into spring, as late as mid-Mpril (Orcutt et al 1977). Lough (1973) observed C. magister larvae in the plankton off the central Oregon coast in late January and early Febuary. In the Pacific Northwest this is the time when net onshore surface transport prevails as previously described. The different morphologies associated with each stage of pelagic crab larvae represent functional adaptations to a planktonic existence which allows for development and disperal. Immediately after hatching there is a short duration (11-60 minutes) proto or prezoeae stage (McKay 1937, Buchanan and Millemmann 1969). During the next few months these larvae metamorphose through five zoeal stages in which their locomotive capacities are very restricted. Knowledge of their vertical location within the water column at different stages of development is important in understanding their spatial distribution and local abundance (Lough 1976). As zoea develop from stage I to stage V, they become progressively heavier and acquire a strong negatively phototaxic response (Cleaver 1949, Gaumer1971). They vertically migrate downward, utilizing outward flowing bottom currents and become displaced farther offshore within a few meters of the bottom (Orcutt et al 1977). The California Fish and Game has recorded zoea stage V 177km offshore. After zoeal stage V, they metamorphose in actively swimming, temporarily photopositive megalopae. Tasto et al (1980) measured megalopae swimming at a rate of 1-2cm/sec. The megalopae "swarm" at the surface between the months of March and June in Southern Oregon waters. The onshore transport of these megalopae "swarms" can be obstructed or facilitated depending on the prevailing current conditions. This mass migration onshore enables the megalopae to remain on the continential shelf, in bays and estuaries until the time has arrived to metamorphose into a juvenile crab.

Molting from a megalopae to a juvenile crab involves keying into some enviromental factor or factors and altering their phototaxic response. Once epibenthic, they bury themselves up to their eyestalks through the use of rapid abdominal undulations (per. ob.), Metamorphosis to a juvenile occurs within days after burial (p.o.). In molting to a juvenile crab the abdomen is folded under along with various other physiological and morphological changes (ref.). After becoming a juvenile crab, molting will occur six times a year for the next two years and then approxiametly once a year thereafter (Butler 1960). Carapiece width is the most often used measurement of age (Butler 1960). In southern Oregon commercial size is obtained 4 to 5 years after ecdysis to a juvenile crab.

MATERIALS AND METHODS

STUDY AREA

The Coos Bay estuary is located in Coos County, Oregon about 200 miles south of the Columbia River and about 445 miles north of San Fransisco Bay at 43.8°N latitude. Coos Bay, a drowned river mouth, is a relatively recent geologic feature which was created by local downwarping of marine sedimentary bedrock (CBEP 1975). It stretches southeast to northeast to south 27 miles and has a gentle sloping bottom with a fairly uniform increase in depth near the mouth. The Division of State Lands (1973) estimates 6200 acres is submersible land (between LW and MLW) and 6180 acres is submerged land (below MLW). The drainage area of Coos Bay is about 820 miles^2 and is rugged, steep slopes rising abruptly from valley floors covered mainly with coniferious forests. There are 30 tributaries of Coos Bay. The primary ones are the Coos and Millicoma Rivers, to a lesser degree Haynes and Kentuck Inlets, Catching, Isthimus, Pony and South Sloughs.

Coos Bay is classified as a deep-draft development by the L.C.D.C. (1977). The bar entrance is maintained through dredging at 40 ft. and the inner channel to 35 ft. with a width of 300ft. Extensive filling and dredging has changed much of the hydrography of Coos Bay. The tidal prism of Coos Bay is $1.86X\ 10^9 ft^3$ based on extreme tidal range (Johnson 1972). Mixing and flow rate of the estuary depends on the constriction at the mouth and its depth. Coos Bay is classified as a type D or well mixed system (McAllister 1959). It varies from partially mixed to vertically homogenous depending on the time of the year. Arneson (1976) noted ebb currents 3.5knots and maximum ebbing at 5 knots. The mean tidal range is 6.7ft. above MLLW at the entrance to Coos Bay (USACE 1978). Extreme Low Water is predicted to be -3.0 ft. below MLLW. The average annual discharge at the mouth is 2.2 million acre ft. of freshwater (Percy et al 1974). The flushing rate is dependent on river discharge, topographical features and the level of coastal upwelling. [illegible] (1976) found that [illegible] upwelling. Armeson (1976) found that even under optimum conditions retention times of several days.

ZOOPLANKTON SAMPLES

Six sample stations were selected using compass readings, aerial photography, triangularization with points on the shoreline and nearby reference bouys (diagram 1). The mouth of the bay was the area of concentration since preliminary sampling indicated that this area would exhibit zooplankton import and export. The equipment consisted of a 30cm standard plankton sampler with a #10 (300micron) nylon mesh net towed by a 7.5 horsepower Mercury outboard engine on an aluminum skiff. Oblique tows to a depth of 3m were taken for two minutes at a speed of less than 5 knots over a standard distance of 25m, using the shoreline and the station bouy as a reference point. The net was washed down after each plankton haul and the contents of each sample placed in 250ml jars preserved in 10% formalin with rosebengle and later transfered to 50% alcohol. For the purposes of identiying general trends from this standardized procedure the sample abundance was taken as the relative bay abundance. Both night and day zooplankton samples were taken between January 20, 1980 to June 20, 1980 and January 10, 1981 to June 20, 1981 at a rate of six times a month. All Samples taken within one hour of high tide were assumed to be measuring relatively equivelent volumes of water. Relative to the tidal conditions, high or low, the remainder of the samples were taken as randomly as possible. Additional presence-absence information was obtained from dip netting off the docks at night.

In the laboratory 100% of all the plankton samples were specifically examined with the purpose of identifying and enumerating the genus Cancer to the species level. Identifying to species was accomplished by using the measurement key provided by Lough (1975), the micrographing keying technique of Deboyd Smith (1975). As a supplement to this, C. magister larvae hatched from ovigerious females in the laboratory were used for comparative purposes. For future reference, larval stages of C. magister were photographed using ASA 64 Kodacolor II under Wild Stereomicroscopic M4 with a Canon FTB Back.

PHYSICAL MEASUREMENTS

Daily sea surface temperatures and densities taken at high tide were obtained near the mouth of the bay from Oregon Department of Fish and Wildlife, Charleston station (Al McGee 1981). Density measurements were taken with a calibrated hydrometer and converted to surface salinities. Temperature was read immediately after sampling with a standard bucket thermometer accurate to .1° C.

Upwelling Indices from 1946 through June 1981 were measured from oceanographic cruises and offshore CALCOF bouys. Only the Upwelling Indices for 42° N,125W and 45 N,125W were used in this analysis of larvae off the Oregon coast. They were calculated from an integration of several enviromental affects: barometric pressure, wind stress, sea level and the local corialis force.

Daily weather patterns: percipitation, wind vector, bar swell, along ocean swell, and barometric pressure were obtained from the U.S. Coast Guard Station at Charleston and the "Climatological Summary" from N.O.A.A. (1980).

CALCULATIONS

Information on coho salmon enhancement and feeding in the Coos Bay estuary was provided by Oregon Aqua Foods (Rob Lawrence 1981), Al McGee (p.c. 1981), Bill Pearcy (p.c.1981).

Data for pounds of crabs landed for Oregon since the 1950-51 season was obtained from the Pacific Marine Fisheries Service and Demory (1981).

The regression analysis program was preformed on the PDP-10 system in the computer center at the University of Oregon.

LARVAE SETTLEMENT EXPERIMENT

Megalopae were collected in the Coos Bay estuary on April 2, 1980 using a standard dip net. All individuals were assumed to be the same age since they were obtained in one "swarm". The megalopae were kept in a holding tank with no substrate to avoid any future biases. The temperature of the holding tank, and selection chamber (diagram 2) was monitored between 11.0 and 14.0° C throughout the entire experiment. The settlement chamber consisted of six compartments with three different types of substrate, a replicate for each, 2 cm in depth. The chamber was encircled by 3/4 m high black plastic tarp to insure equal lighting in each compartment. Megalopae could freely swim between compartments testing each substrate provided until ecdysis to a juvenile crab. Partitions were sufficient to prevent 1st instars from migrating between compartments. The megalopae were then introduced in equal amounts to each compartment to avoid any bias of origin. Orcutt et al (1977) larval rearing experiments demonstrated that 20 or less megalopae per liter was sufficiently low enough density level to yield high survival rates. In this experiment only 2 individuals per liter were used in each repitition to prevent complications from density interference. Every 48 hours 25 ml of cultured brine shrimp was placed at the surface of each compartment. The water flow at both outlets was kept at 5ml/sec. At intervals of 10 hours the number of 1st instars and molts in each compartment was counted and removed. Regular removal was deemed necessary due to cannabalistic behavior of C. magister.

Between repititions of the selection experiment, all substrates were removed and replaced with similiar sediments, only in altered locations within the box. Altering sediment position subtracted statistical problems associated with the non-random cornering effect, water flow and other variables. Throughout the entire experiment behavioral patterns were observed in association with selection and metamorphosis to a juvenile crab.

Chi-sqed statictics were employed to analyze the degree of non-random selection and implied sediment preferences.

RESULTS

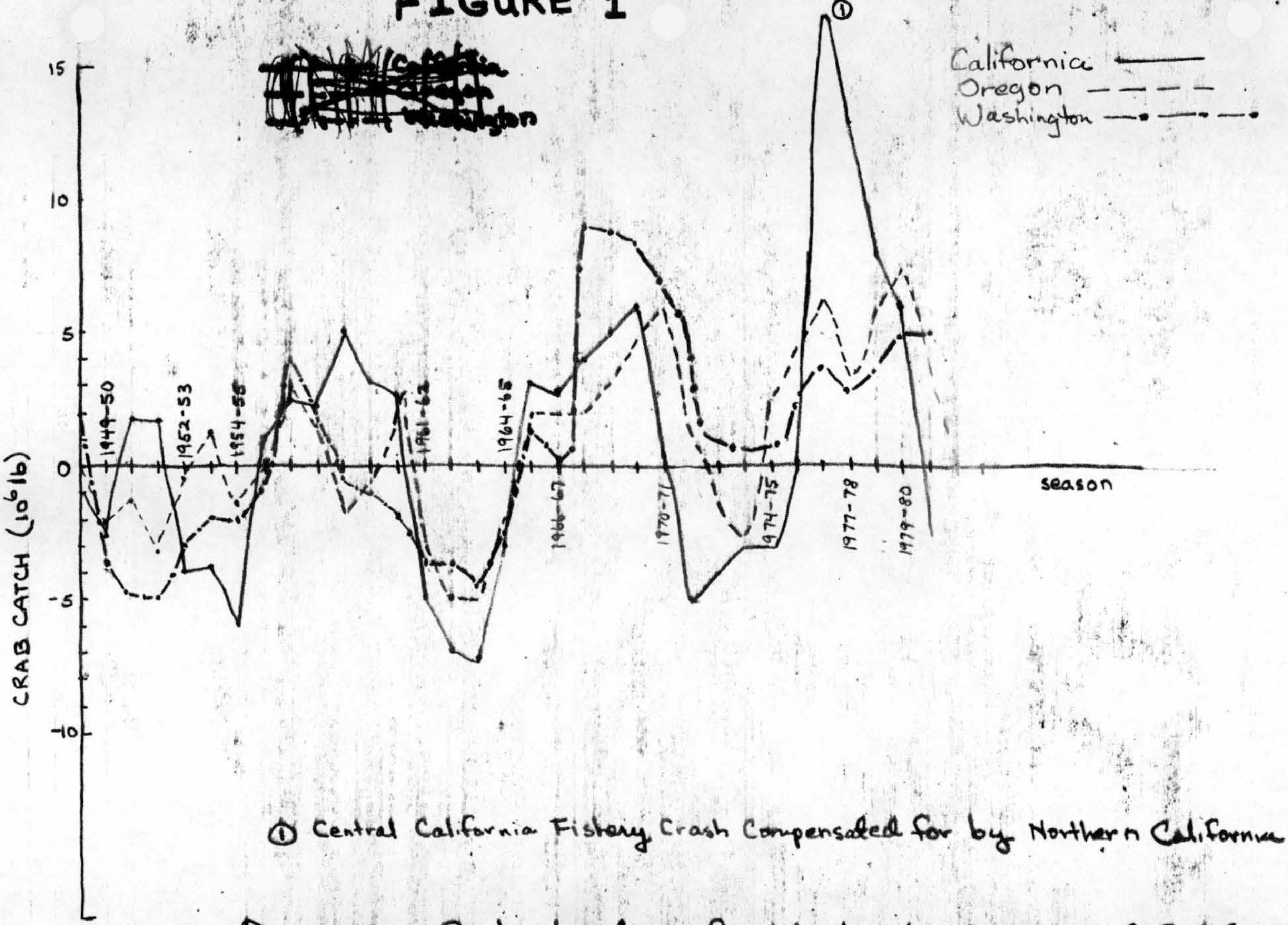
Unusually warm sea surface temperatures were detected in the Coos Bay estuary during January, Feburary, and March of 1981 (Figure 3). The onset of consistently strong upwelling occured later in 1981 (Figure 3 and p.c. Al MeGee). Generally, there is a two to three day lag in response of bay sea surface temperaure to coastal upwelling (Figure 3).

I was unable to compare statistically the catch-per-unit-effort of the D geness crab larvae samples; yet the differences in timing and abundance between 1980 and 1981 appear to be considerable but not consistent. When evaluating the two years by success of night capture, 1980 appears to be a stronger year-class recruitment. Capture of only zoeal stages I,II and mega- in the bay agrees with what is known about their dispersal during development.

The statistical analysis on the megalopae settlement experiment demonstrates that settlement preferences were not random Tables 3-7). Course well-sorted sand typical of open coast beaches appeared to be their prefered settling habitat. Behavioral observations concluded that the thixotropic properties of the sediment-type was the settlement determinate. The low mortality levels during the culturing indicated a suitable enviroment and the feasibility of an enhancement program.

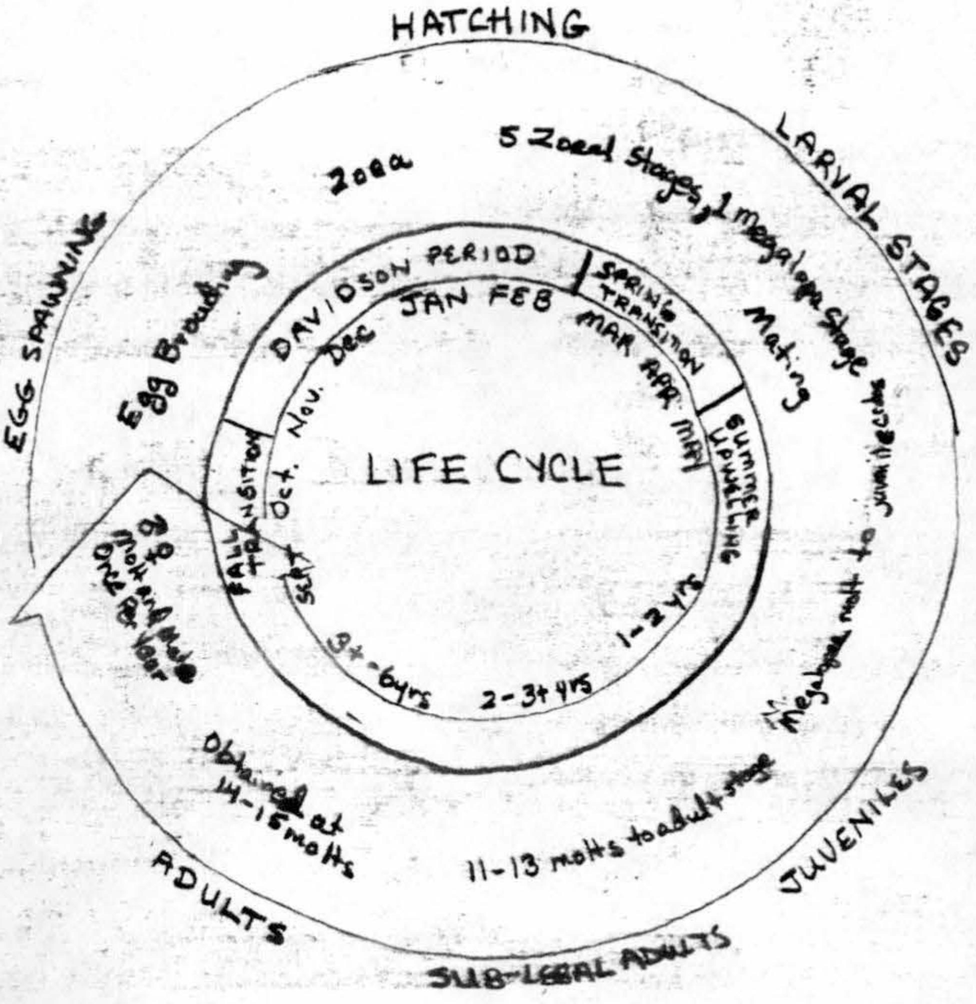
The Upwelling Indices, during the megalopae stage, correlated with a four year-lagged crab catch by -.673, F level 57.52 with 28 degrees of freedom.

FIGURE 1



① Central California Fistery Crash Compensated for by Northern California Catch

Dungeness Crab Landings for Washington, Oregon and California
(From P.M.F.C. Data Series) - Darold Demory - Marine Science Center



TEMPORAL SEQUENCES OF *Cancer Magister's* Life History AND NEARSHORE CURRENTS OFF SOUTHERN OREGON

FIGURE 2

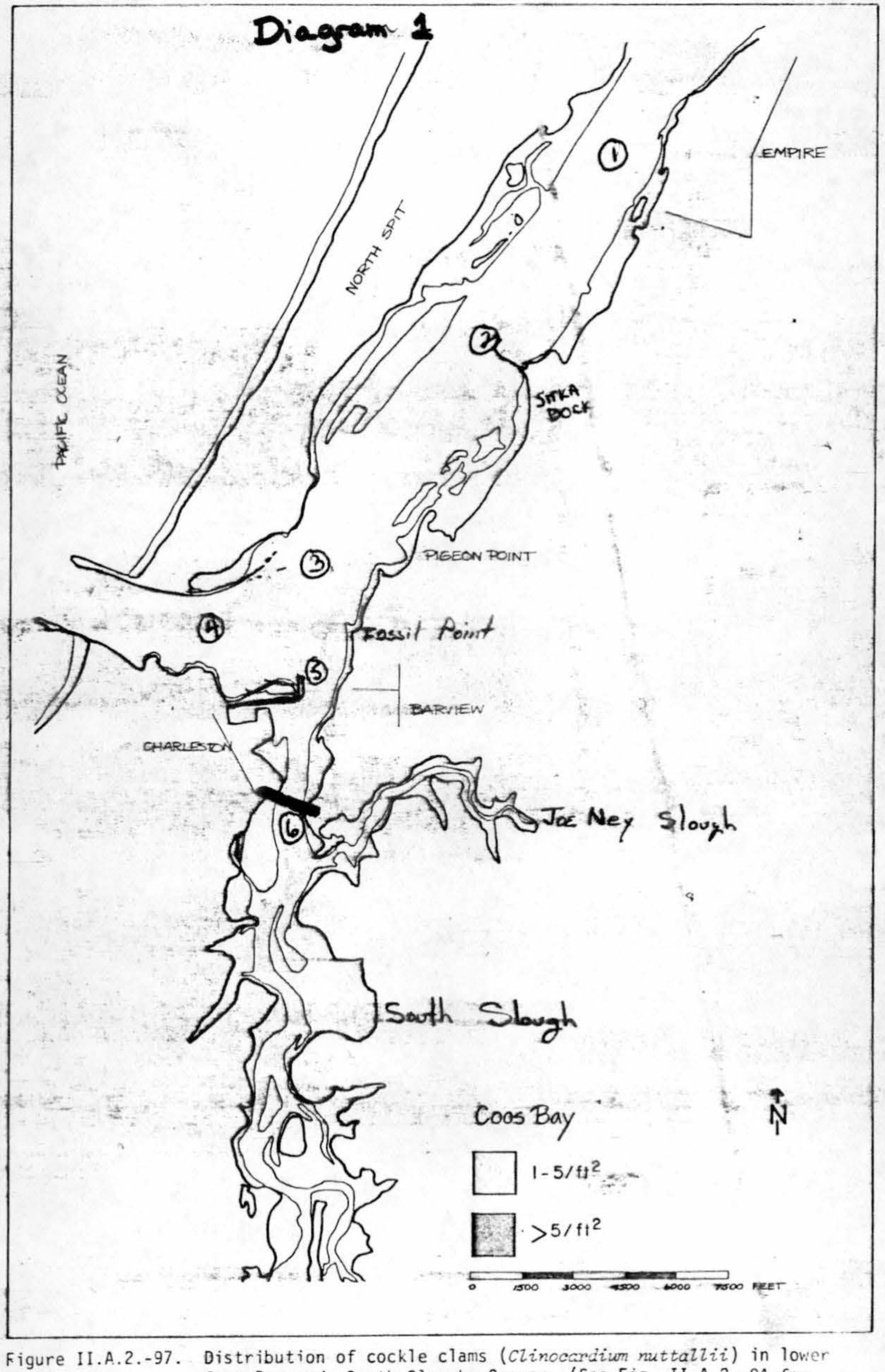
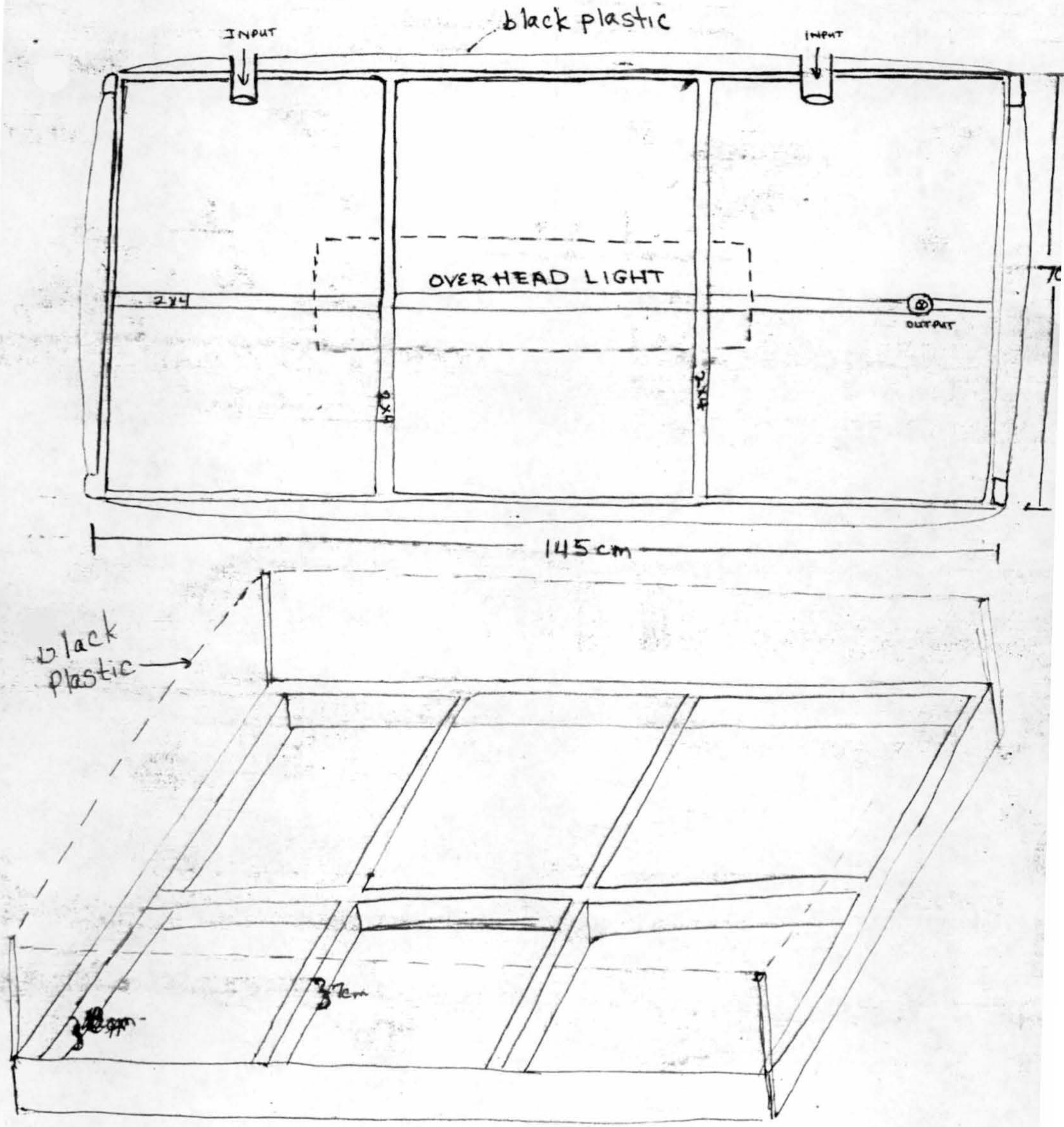


Figure II.A.2.-97. Distribution of cockle clams (*Clinocardium nuttallii*) in lower Coos Bay and South Slough, Oregon. (See Fig. II.A.2.-94 for areas not surveyed.)



13cm x 145cm x 70cm ≛ 105 liters

SELECTION Aquarium Diagram #2

FIGURE 5A

1980 UPWELLING INDI VS. BAY SEA SURFACE TEMPERATURE

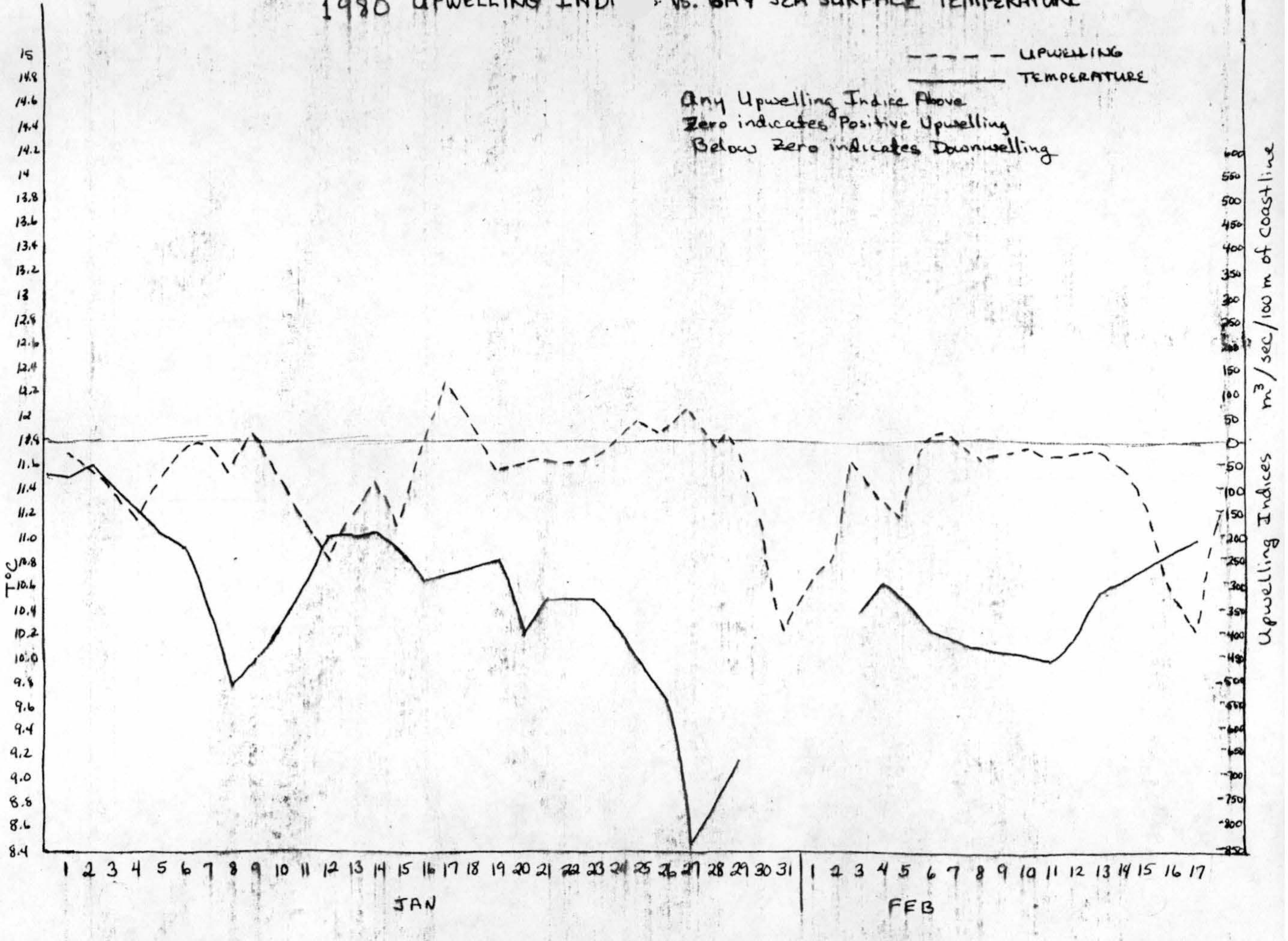


FIGURE 5B

1980 UPWELLIN[illegible]. SEA SURFACE TEMPERATURE

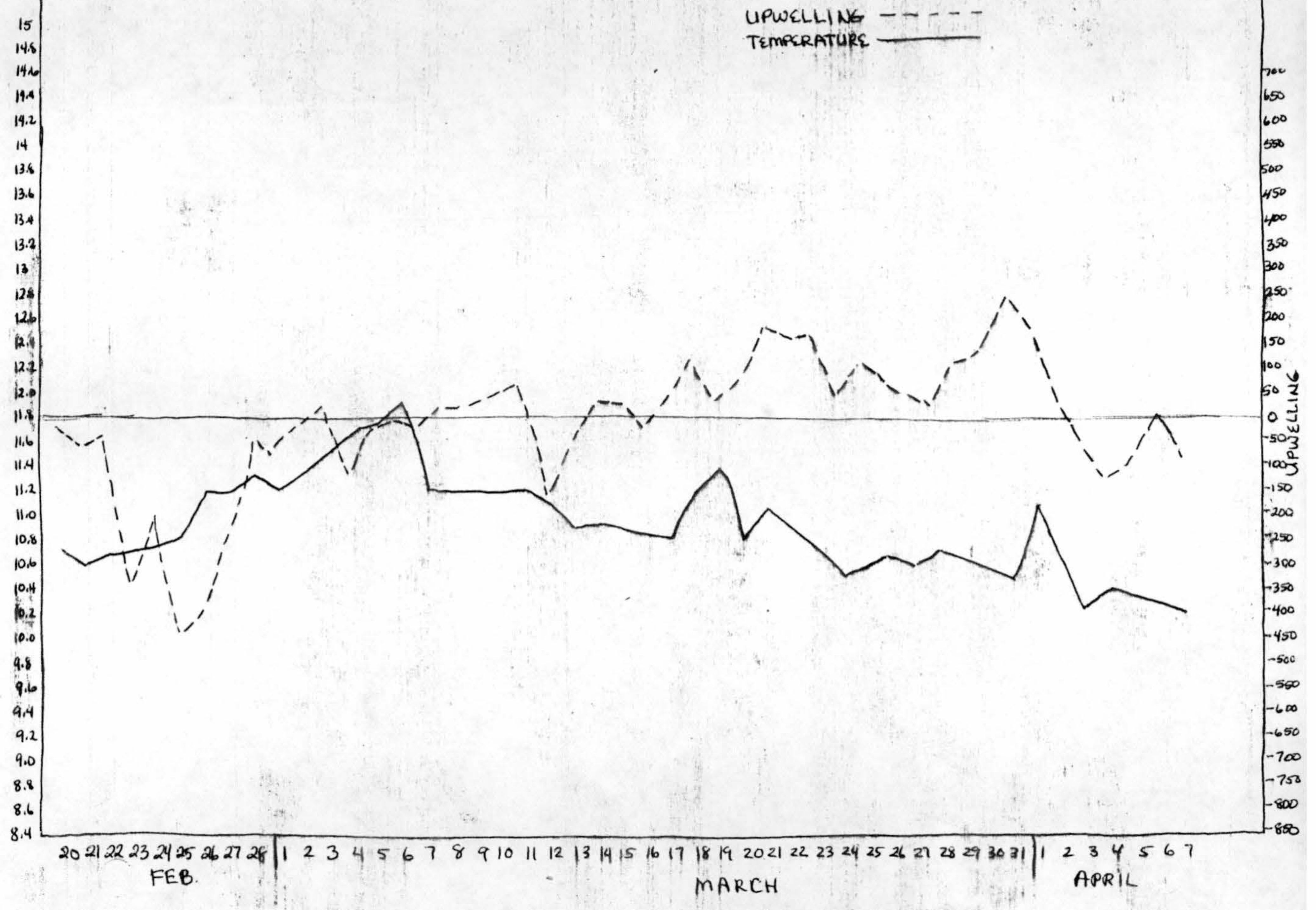


FIGURE 3C

1980 UPWELLING vs. [illegible]A SURFACE TEMPERATURE

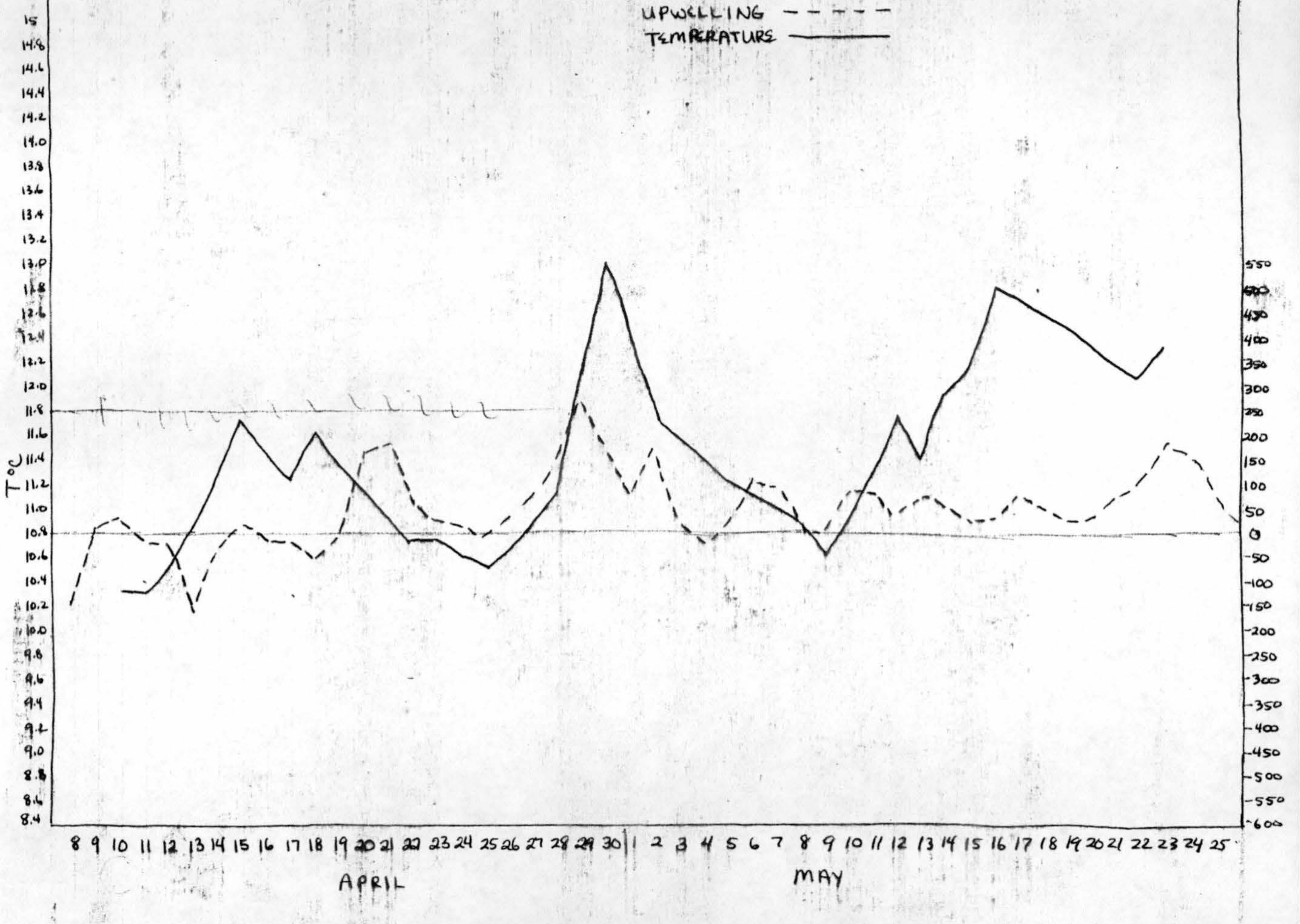


FIGURE 3D 1981 UPWELLING INDICES vs. BAY SEA SURFACE TEMPERATURE

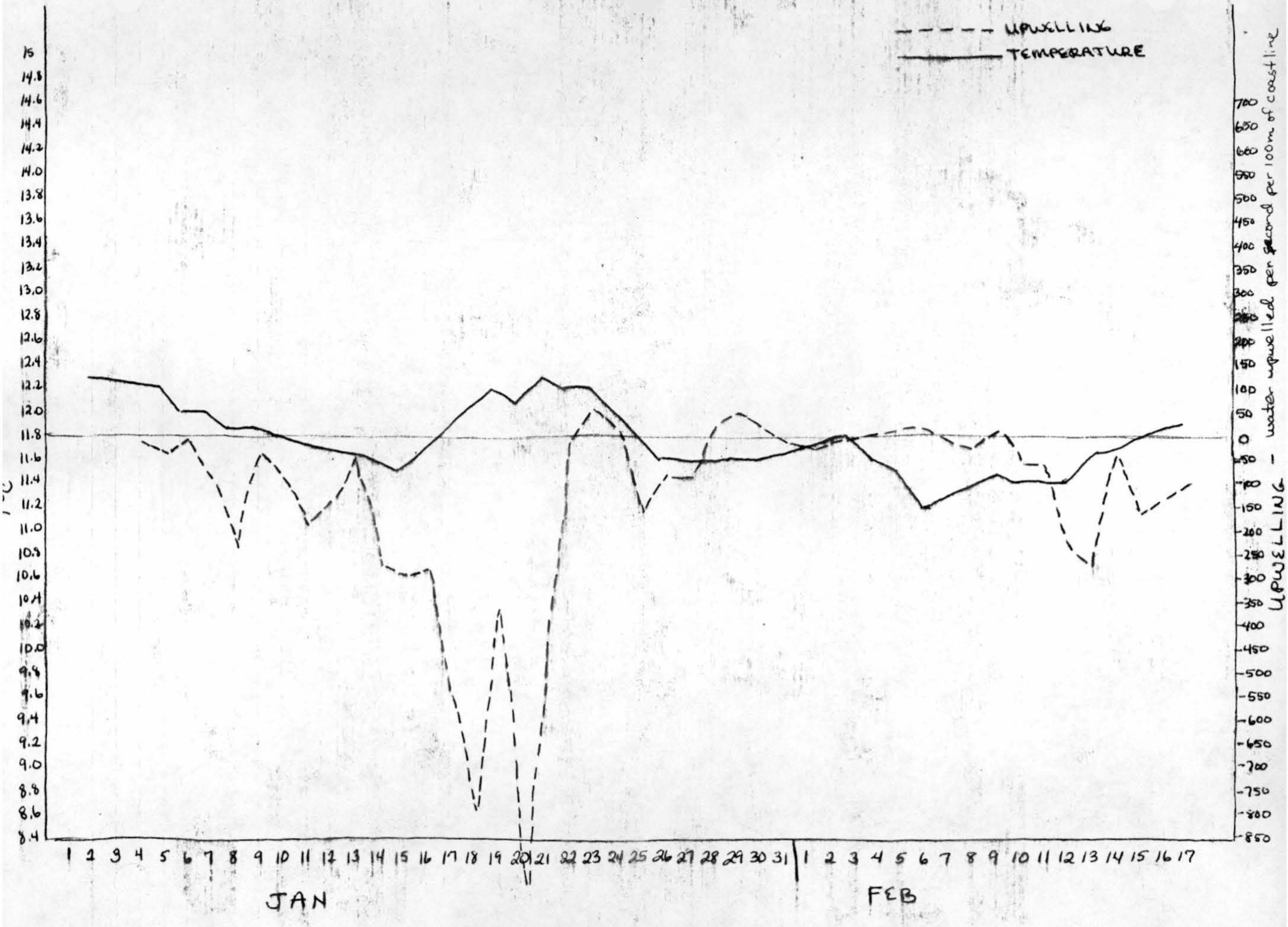


FIGURE 3E 1981 UPWELLING I[illegible]ICES vs. SEA SURFACE TEMPERATURE

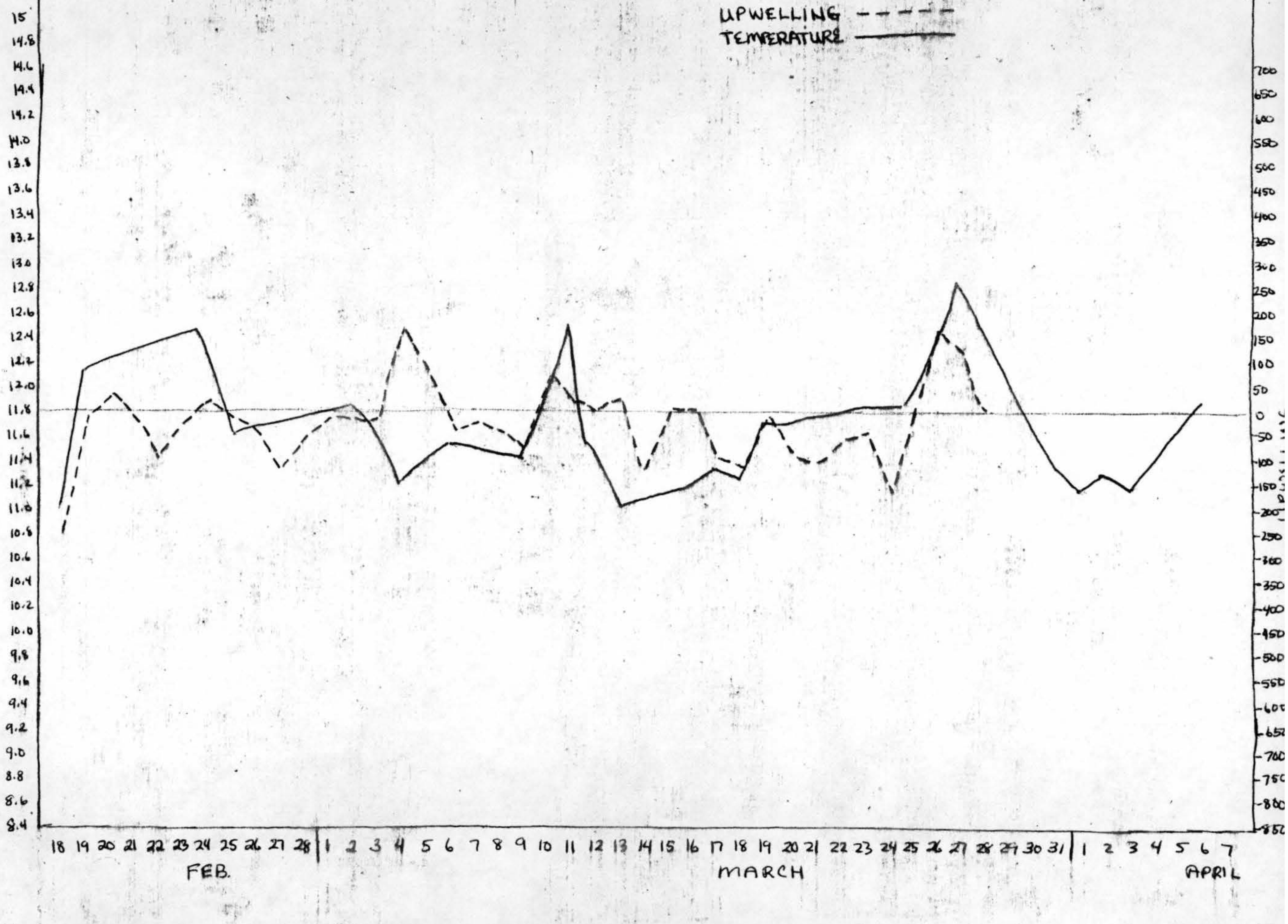
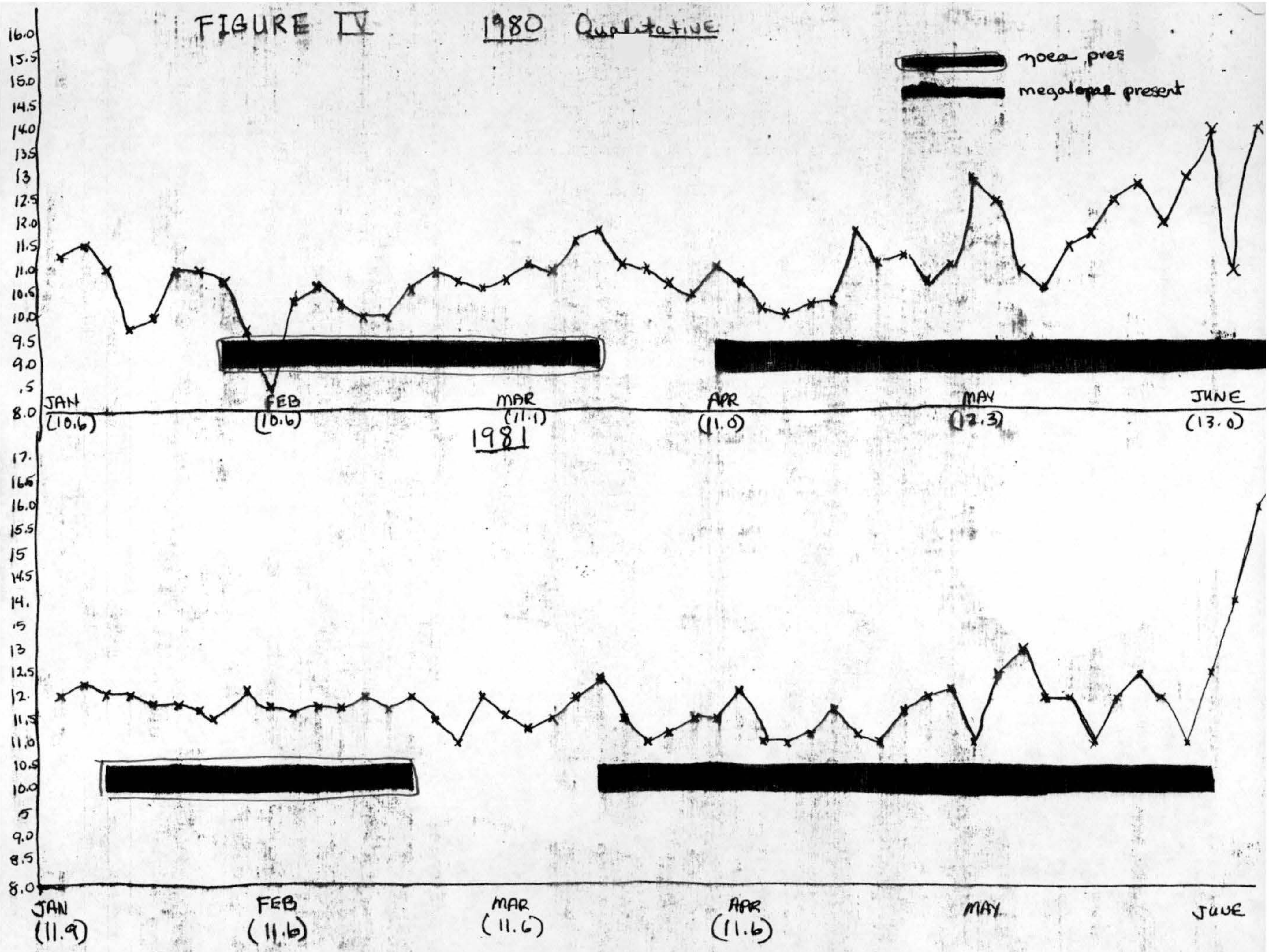


FIGURE IV



( ) - temp. monthly mean

FIGURE 5

1980 & 1981 [illegible]
DAY vs. NIGHT TOWS*

*all plankton hauls taken within 1 hour before h[illegible] tide.

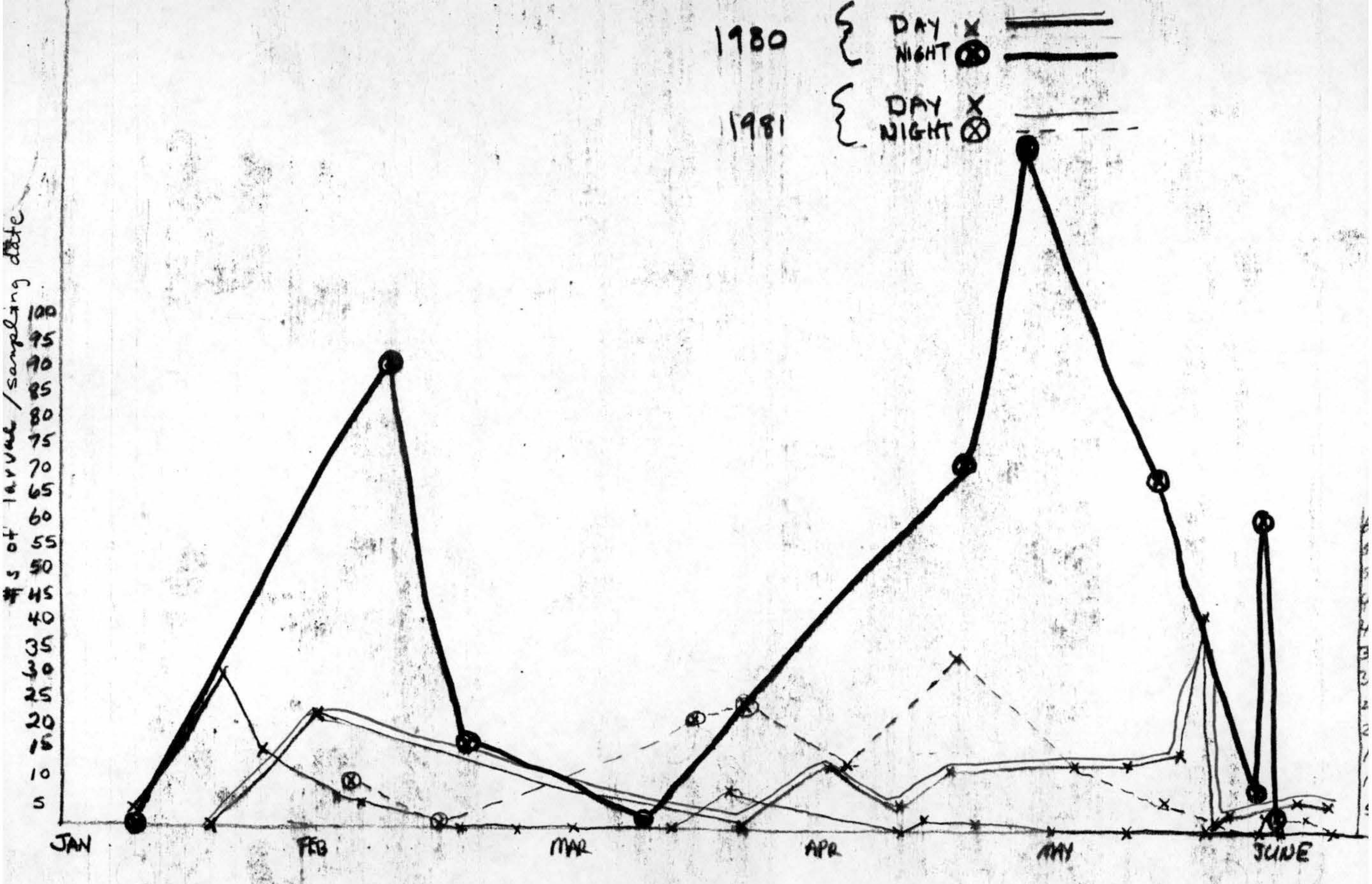


TABLE 1

PREDATORS ON CANCER MAGISTER MEGALOPAE

Scientific Name	Common Name
Glyptocephalus zachirus	rex sole
Leptocottus armatus	staghorn sculpin
Platichthys stellatus	starry flounder
Parophrys vetulus	English sole
Onchorynchus kisutch	Silver salmon

TABLE 2

PREDATORS ON CANCER MAGISTER JUVENILES

Scientific Name	Common Name
Scoraenichthys marmatus	cabezon
Platichthys stellatus	starry flounder
Leptocottus armatus	staghorn sculpin
Raja binoculata	big skate
Glyptocephalus zachirus	rex sole
Sebastes caurinus	copper rockfish
Citharichthys sordidus	Pacific sandab
Hexagrammus decagrammus	kelp greenling
Lepidopsetta bilineata	rock sole
Parophrys vetulus	English sole
Amphistichus rhodoterus	redtail surfperch
Damalichthys vacca	pile surfperch
Merluccius productus	Pacific hake
Acipenser medirostris	green sturgeon
Triakis semifasciata	leopard shark
Myliobatis califorica	bat ray
Phanerodon furcatus	white surfperch

Information provided by Orcutt et al 1975-1977.

TABLE 3 MEGALOPAE Settlement -

ECTION	4/14 12 midnight	4/15 10am	4/15 8pm	4/16 6am	4/16 4pm	4/17 2am	4/17 12 noon	4/17 10pm	4/18 8am	4/18 6pm	4/19 8am	Total
3A	0	13	8	5	0	0	1	2	3	3	0	35
3B	0	2	6	21	6	1	1	9	5	6	4	61
2A	0	8	5	2	7	1	21	1	5	3	0	53
2B	0	1	1	8	2	0	2	3	5	3	0	25
1A	0	0	1	2	0	0	2	4	0	3	2	14
1B	0	2	2	0	1	0	3	0	0	2	2	12
total	0	26	23	38	16	2	30	19	18	20	8	200 *

SEDIMENT TYPE

	# of 1st instars	location	description
1	26	Off Jetty Charleston	course-well sorted hard packed
2	78	Off Portside →	poorly sorted fine, organics
3	96	BASTENDORF →	well sorted course very fluffy

Compartment Arrangement

1B (12)	2B (25)	3B (61)
3B (35)	1A (14)	2A (53)

( ) - #s of instars

* - note no mortalities

RESULTS Experiment #1

TABLE 4

SEDIMENT	(1) observed frequency f	(2) expected freq. $\hat{f}$	(3) Deviation $f-\hat{f}$	(4) Dev.^{2} $(f-\hat{f})^2$	(5) $\frac{(f-\hat{f})}{\hat{f}}$
1 (Charleston Jetty)	26	66.666	−40.666	1653.72	63.6047
2 (PortsiDE)	78	66.666	11.334	128.45955	1.6469
3 (BASTENDORF)	96	66.666	30.666	940.40	9.7958

degrees of freedom (n = # of variables) χ^2 = 75.0474
n − 1 = 2

Chi-sq Contengency TABLE Experiment # 1

ECTION	10pm	8am	6pm	2am	12noon	10pm	8am	6pm	2am	12noon	Total
3A	5	2	1	3	4	2	0	1	5	6	29
3B	6	1	0	4	3	1	4	3	2	1	25
2A	2	0	0	0	1	0	4	3	0	3	13
2B	5	2	0	3	3	2	3	2	1	3	14
1A	0	0	1	0	0	2	0	1	0	0	4
1B	1	0	1	0	0	0	3	0	0	0	5
otal	19	5	3	10	11	7	14	10	8	13	100

SEDIMENT TYPE	# of 1st instars	location	description
1	9	off charleston jetty	course, well sorted hard packed
2	37	MiddleCove	dark, course, well sorted
3	54 (1 dead)	Bastendorf	well sorted, course, very fluffy

Compartment Arrangement

2B (14)	3B (25)	1B (5)
1A (4)	2A (13)	3A (29)

TABLE 5 Results Settlement Exp #2 ( ) - # of instars

EDIMEN	(1) observed frequency f	(2) expected freq. $\hat{f}$	(3) $f-\hat{f}$	(4) $(f-\hat{f})^2$	$\frac{(f-\hat{f})^2}{\hat{f}}$
1 (Charleston Jetty)	9	33.333	-24.333	592.094	17.763
2 (Middle Cove)	37	33.333	3.667	13.4468	0.4034
3 (BASTENDORF)	54	33.333	20.667	427.124	12.8138

degrees of freedom = 2
n-1

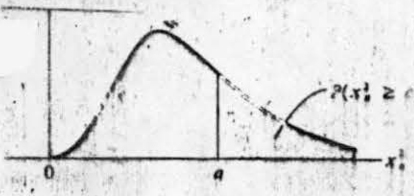
$\chi^2 = 30.98$

Chi-sq Contengency TABLE Experiment #2

TABLE 6 - MEGALOPAE SETTLEment

Table A-4 Values of chi-square for various degrees of freedom

Examples. The probability that a χ^2 random variable with 15 degrees of freedom exceeds 22.31 is $P(\chi^2_{15} \geq 22.31) = 0.10$. (b) The table shows that $P(\chi^2_{10} \geq 15)$ lies between 0.10 and 0.20. Interpolation gives $P(\chi^2_{10} \geq 15) = 0.14$, approximately.



is this identical with

acceptable

Degrees of freedom	Probability levels													
	0.99	0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.05	0.01	0.001
1	0.00	0.00	0.02	0.06	0.15	0.27	0.45	0.71	1.07	1.64	2.71	3.84	6.63	10.83
2	0.02	0.10	0.21	0.45	0.71	1.02	1.39	1.83	2.41	3.22	4.61	5.99	9.21	13.82
3	0.11	0.35	0.58	1.01	1.42	1.87	2.37	2.95	3.66	4.64	6.25	7.81	11.34	16.27
4	0.30	0.71	1.06	1.65	2.19	2.75	3.36	4.04	4.88	5.99	7.78	9.49	13.28	18.47
5	0.55	1.15	1.61	2.34	3.00	3.66	4.35	5.13	6.06	7.29	9.24	11.07	15.09	20.52
6	0.87	1.64	2.20	3.07	3.83	4.57	5.35	6.21	7.23	8.56	10.64	12.59	16.81	22.46
7	1.24	2.17	2.83	3.82	4.67	5.49	6.35	7.28	8.38	9.80	12.02	14.07	18.48	24.32
8	1.65	2.73	3.49	4.59	5.53	6.42	7.34	8.35	9.52	11.03	13.36	15.51	20.09	26.12
9	2.09	3.33	4.17	5.38	6.39	7.36	8.34	9.41	10.66	12.24	14.68	16.92	21.67	27.88
10	2.56	3.94	4.87	6.18	7.27	8.30	9.34	10.47	11.78	13.44	15.99	18.31	23.21	29.59
11	3.05	4.57	5.58	6.99	8.15	9.24	10.34	11.53	12.90	14.63	17.28	19.68	24.72	31.26
12	3.57	5.23	6.30	7.81	9.03	10.18	11.34	12.58	14.01	15.81	18.55	21.03	26.22	32.91
13	4.11	5.89	7.04	8.63	9.93	11.13	12.34	13.64	15.12	16.98	19.81	22.36	27.69	34.53
14	4.66	6.57	7.79	9.47	10.82	12.08	13.34	14.69	16.22	18.15	21.06	23.68	29.14	36.12
15	5.23	7.26	8.55	10.31	11.72	13.03	14.34	15.73	17.32	19.31	22.31	25.00	30.58	37.70
16	5.81	7.96	9.31	11.15	12.62	13.98	15.34	16.78	18.42	20.47	23.54	26.30	32.00	39.25
17	6.41	8.67	10.09	12.00	13.53	14.94	16.34	17.82	19.51	21.61	24.77	27.59	33.41	40.79
18	7.01	9.39	10.86	12.86	14.44	15.89	17.34	18.87	20.60	22.76	25.99	28.87	34.81	42.31
19	7.63	10.12	11.65	13.72	15.35	16.85	18.34	19.91	21.69	23.90	27.20	30.14	36.19	43.82
20	8.26	10.85	12.44	14.58	16.27	17.81	19.34	20.95	22.77	25.04	28.41	31.41	37.57	45.31
21	8.90	11.59	13.24	15.44	17.18	18.77	20.34	21.99	23.86	26.17	29.62	32.67	38.93	46.80
22	9.54	12.34	14.04	16.31	18.10	19.73	21.34	23.03	24.94	27.30	30.81	33.92	40.29	48.27
23	10.20	13.09	14.85	17.19	19.02	20.69	22.34	24.07	26.02	28.43	32.01	35.17	41.64	49.73
24	10.86	13.85	15.66	18.06	19.94	21.65	23.34	25.11	27.10	29.55	33.20	36.42	42.98	51.18
25	11.52	14.61	16.47	18.94	20.87	22.62	24.34	26.14	28.17	30.68	34.38	37.65	44.31	52.62
26	12.20	15.38	17.29	19.82	21.79	23.58	25.34	27.18	29.25	31.79	35.56	38.89	45.64	54.05
27	12.88	16.15	18.11	20.70	22.72	24.54	26.34	28.21	30.32	32.91	36.74	40.11	46.96	55.48
28	13.56	16.93	18.94	21.59	23.65	25.51	27.34	29.25	31.39	34.03	37.92	41.34	48.28	56.89
29	14.26	17.71	19.77	22.48	24.58	26.48	28.34	30.28	32.46	35.14	39.09	42.56	49.59	58.30
30	14.95	18.49	20.60	23.36	25.51	27.44	29.34	31.32	33.53	36.25	40.26	43.77	50.89	59.70
50	29.71	34.76	37.69	41.45	44.31	46.86	49.33	51.89	54.72	58.16	63.17	67.50	76.15	86.66
100	70.06	77.93	82.36	87.95	92.13	95.81	99.33	102.9	106.9	111.7	118.5	124.3	135.8	149.4
200	156.4	168.3	174.8	183.0	189.0	194.3	199.3	204.4	210.0	216.6	226.0	234.0	249.4	267.5
500	429.4	449.1	459.9	473.2	482.9	491.4	499.3	507.4	516.1	526.4	540.9	553.1	576.5	603.4
800	709.9	735.4	749.2	766.2	778.6	789.2	799.3	809.5	820.5	833.5	851.7	866.9	896.0	929.3
1000	898.9	927.6	943.1	962.2	976.1	988.1	999.3	1011.	1023.	1037.	1058.	1075.	1107.	1144.

TABLE 7 Statistics TABLE

TABLE 8

CALCULATIONS OF POTENTIAL PREDATION PRESSURE ON *CANCER MAGISTER* MEGALOPAE IN COOS BAY FROM SALMON ENHANCEMENT

1) 10×10^6 salmon smolts weighing averaging 22 grams released between March and July

2) 20 days in bay complex, feeding at a maximum rate of 3 megalopae per day

3) Therefore, 30×10^6 megalopae consumed per day for 20 days = a total of 6×10^8 megalopae consumed.

4) $.5 \times 10^6$ larvae produced per female crab.

5) $\frac{6 \times 10^8 \text{ megalopae}}{.5 \times 10^6 \text{ larvae per female}} = 12 \times 10^2$ female's offspring

Therefore, feeding on the potential of 1200 mature female's offspring

DISCUSSION

SAMPLING ANALYSIS

The zooplankton sampling indicated that in 1981 the onset and duration of each larval stage was accelerated relative to 1980. Megalopae were obtained two weeks earlier in 1981(Figure IV). The Coos Bay and nearshore sea surface temperatures for the 1981 larval season were consistently higher than in 1980 and for previous years (Figure 3). The Q_{10} , physiological response of organisms to temperature change is well documented (ref.). The anticipated affect of an increase in ambient temperature would be this shortened larval existence (p.c. R. Tasto). A shortened duration of planktonic existence, theoritically, decreases the overall predation pressure. If the larval stages are completed before the onset of upwelling than this could substantially decrease the probability of dispersal to an unfavorable habitat, off the contential shelf. Larval metabolic demands increase due to elevated ambient temperature. This elevated temperature is associated with relatively unproductive waters of the Davidson Current. Hypothetically, intra and interspecific larval competition for consumption of a depauperate supply of phyto and nannoplankton could become an important determinate of survival rates. To substantiate this hypothesis, gut-fullness of C. magister larvae needs to be analyzed to determine if food is a limiting resource.

Day-night sampling variability is a function of diurnal vertical migration. Day-night differences in plankton sampling is a well established phenomena due to behavioral responses to light. The results of my sampling clearly indicate a much greater success rate at night, but the differences are not statistically significant (Figure 5). Even with day-night duplicate tows which eliminates some of the temporal variablity, the sampling success was greater at night. Whether this mechanism of diurnal vertical migration is an adaptation evolved to avoid visual predation, to feed on a preferred nocturnal prey or to avoid daily wind-driven offshore surface flow has not been determined.

In the Coos Bay estuary the tidal influence was clearly the major factor in determing capture success. The probability of obtaining *C. magister* larvae was greatest at or near high tide. The frequency of encountering a megalopae "swarm" increased substantially around spring high tides when a greater volume of water entered the bay. The combined speed of the megalopae and the surface water enabled individual "swarms" to reach areas 20km up the estuary before the ebbing tide. Many 1st instar juvenile crabs were found in the shallow reaches up the bay indicating larvae settlement and ecdysis had occured. This tidal affect dominates surface transport once the megalopae "swarms" congregate within 5km of bay entrances. However, the prevailing surface current, as previously described, determines arrival to these nearshore coastal waters (Lough 1976).

CYCLIC FLUCTUATIONS IN CRAB CATCH

Commercial crab landings, represent an estimated 90 to 100% of the total number of legal males. Thus we can consider that the crab catch removes a constant proportion of the male population each season and the total pounds landed to be a good index of population size (Orcutt et al 1975). Fluctuations in recent Dungeness crab catches are cyclic with periods of 9 years in California and 12 years in Oregon and Washington (Botsford andWickham 1975). This indicates a generation time of 4.5 years in California and 5-6 years in Oregon (Figure 1). The possible mechanisms driving this cyclic phenomena are of primary importance to fisheries biologists. Hypotheses recently examined include density-dependent interactions (Botsford and Wickham 1975,1978,1979), density-independent effects on larvae survival (Lough 1974), temperature-related hatching success (Mayer1973, Wild et al 1978 and Wild & Haugen 1979) and egg predators (Wickham & Fisher 1977, Wickham 1979b, 1979c).

These fluctuations in crab catch occur uniformly along the entire west coast of the United States. This indicates that some major coast-wide enviromental change is responsible for the fluctuations in the adult year-class strength. Lough (1975) suggested that the strength of the Dungeness year-class is largely determined by enviromental conditions during the critical larvae stages, the number of pelagic crab larvae surviving planktonic existence is directly proportional to the size of the subsequent adult population. The hypothesis I explored was that seasonal changes in surface water circulation patterns combined with inter-year diffences in larval timing could result in dispersal of crab larvae into unfavorable settling habitats, thusly reducing overall recruitment. This high mortality and low stock recruitment would be reflected in a relatively poor adult year-class strength four to five years later, the time necessary to obtain legal size (Butler 1960). Winnor (1966) concluded that sea surface temperatures reflected ocean currents which transported larvae away from habitats suitable for settling. Upwelling Indices provided by Bakun(1973) indicate the dominant current conditions governing surface water transport. Prior analyzes have utilized the Upwelling Indices as a measure of food production and ultimately growth and survival of existing stocks (Botsford and Wickham 1975, Peterson 1973). These studies would anticipate a relatively strong year-class associated with high upwelling. My hypothesis would equate a favorable year as being characterized by strong downwelling during the megalopae stage, increased onshore transport to favorable enviroments and subsequently enhancing the stock recruitment. Lough (1975) found that the downwelling index contributed very little to reducing the variablity in the crab catch. However, no comparison was made between the crab catch and the downwelling occuring only during the megalopae stage. The correlation coefficient for this statistical regression I preformed was -.673. This means that approxiametly 40% of the variance in crab catch could be accounted for by the degree of onshore-offshore transport or some associated variable during the megalopae stage. The Upwelling Indices have a different periodicity and amplitude than the 9-12 year cyclic fluctuation in the crab catch. This indicates that the effect of a set of undiscovered variables are creating what at the present time appears to be a "natural" fluctuation. However, this correlation is surprizeingly strong when one considers the numerous sources of error. First, the data used by Bakun (1973) to calculate Upwelling Indices were taken from five different sources covering the time periods Jan. 1946- March 1955, April 1955-Dec. 1959, Jan. 1960- June 1962, July 1962- Dec. 1971, and Jan 1972- June 1981. Second, the crab catch effort has not remained relatively constant over the past 35 years. Third, this comparison discounts mortality in the pre-legal crab stages. Correlation coefficient is used to measure the intensity of association and does not indicate a causative factor. The causal mechanism may be a series of complex intercorrelated factors. Therefore, this finding provides and indication of certain density-independent interactions requiring further investigation.

Aid in onshore transport of megalopae is provided by the colonial nuestonic hydroid Vellela vellela (Tasto et al 1977, Wickham 1979a). The opportunistic megalopae are provided with a redially available food source, hydroid tenacles, and shelter from planktivores (Abbiott 1980). Strong years of V. vellela washing up on the Oregon beaches, between March and June, are equated with strong southwesterly winds and Davidson Current. Possibly, the relationship between downwelling and crab catch generated in my analysis is actually demonstrating a correlation between strong years of crab recruitment resulting from strong years of V. vellela.

Density-dependent interactions include predation, both natural and human, cannabalism and intra & interspecific competition for food and/or space. The source of natural predation pressure varies correspondingly with developmental and behavioral changes of C. magister through its larval, juvenile and adult stages. Seasonal and diurnal vertical migration during the larval stages dictates their temporal and spacial availability as a prey item. During the first two zoea stages these larvae are photopositive, drifting on the surface nearshore, in bays and estuaries (ref.). The stomachs of surface feeding microzooplanktoners such as surfsmelt, herring and many juvenile rockfish sampled in the Coos Bay estuary contained a high proportion of stage I and II crab zoea. As development proceeds to the later zoeal stages III, IV and V, they become negatively phototaxic, (c.F&G Ref.) descending to the offshore flowing bottom currents. During these stages, demersal feeding fishes such as sculpins, skates, and flatfish along with benthic feeding invertebrates; crabs annelids and bivalves are the major sources of predation pressure. Ecdysis into a megalopae results in a complete reversal of phototactic response. In southern Oregon between March and June the megalopae, being photopositive, are "swarming" at the surface and migrating onshore. Because of the increased size of the Cancer magister larvae in the megalopae stage, the predation pressure shifts to surface feeding fish morphologically adapted to engulf macrozooplankton (Table 1). These "swarms" of megalopae attract large flocks of actively feeding marine birds resulting in high mortality levels. Stomach analysis of a large number of marine birds is deemed necessary to determine the level of impact associated with this predation pressure.

Metamorphosis to the 1st juvenile instar, April-July, limits the source of predation pressure to epibenthic feeding organisms (Table 2). Orcutt et al (1977) postulates that the relative strengths of year-classes of C. magister is reflected in the frequency of occurance of juveniles in fish stomachs. Because of the large number of natural predator species of *C. magister*, throughout its life cycle, a fairly constant level of predation is maintained. Therefore, natural predation does not seem to be a driving mechanism behind the fluctuating crab population levels. However, recent increases in salmon enhancement, along the west coast, could exert additional predation pressure. In 1981 there will be approxiametly 60 million coho salmon smolts released, which is double the numbers released in 1980. Hatchery coho smolts are released between the months of March and June in the bays and estuaries of southern Oregon. This timing corresponds with the onshore migration of the megalopae "swarms". Myers (1975) showed that hatchery coho prefer megalopae when available. Table 8 provides theortical calculations of the potential predation prssure of hatch-coho on *C. magister* megalopae in the Coos Bay estuary.

Human predation can not be the direct cause of these cycles since commercial and sports fishing removes large males that have previously mated. However, human predation does respond to variable abundance levels and in this respect may alter the characteristics and stability of these "natural" cycles (ref.). Certain fishing practices such as not returning to the water numerous sublegal crabs could have a substantial impact on recruitment to commercial stocks. Recent scalloping practices have directly interfered with the crabbing industry. Scallop dragging has damaged numerous crab pots, interfering with catch per unit effort efficiency. The scallop beds represent a potentially excellent food supply and shelter for adult crabs. The high ratio of mature, recently ovigerious, females indicates that they utilise the scallop beds as spawning sites. Pertebation of these sites during or prior to the spawning season could directly affect the reproductive capacity of the crab population.

Cannabolism of both the larval and juvenile stages of *C. magister* could accentuate existing cycles in the crab population , particularly in years of high crab recruitment and a relatively depleted food resource. Knudsen (1960) has designed models of a population's age structure governed by cannabilism.

Intraspecific competition for food and space operates in a density-dependent manner. However, space availability does not appear to be a limiting resource since C. magister adults & juveniles prefer but do not require course-well sorted sand characteristic of exposed open coast areas. Specifically, within the confines of estuaries and bays this type of sediment may be limiting due to increased number of piers, jetties and docks obstructing wave action. Because of C. magister's diversity of prey items, throughout its life cycle, food availability does not appear to be a driving mechanism behind these observed population cycles.

Interspecific competition between Cancer sp. during the larvae stages could be an important factor affecting crab abundance four to five years later. The timing of larval hatching is critical to survival levels. For example, if potential competitors such as C. productus and C. organesis larvae were to hatch several weeks prior to C. magister larvae, then this may more than compensate for their relatively smaller sizes at all stages. This advantage could allow them to outcompete C. magister for available food items. Brooks and Dodson (1965), studying antagonistic effects of mutually shared food resources, concluded that the larger species would outcompete the smaller species without significant pressure from size dependent predation. As an adult the variable dimensions of its fundemental niche would act to minimize interspecific competition.

Density-independent factors which affect larvae survival were examined by Lough (1975) and Orcutt et al (1976). Lough (1975) preformed response surface analysis of temperature and salinity interactive affects upon C. magister survival. These studies showed that in the laboratory variable salinities resulted in immediate mortality whereas the effect of temperature became increasingly important with time. Prior to offshore drifting, early larval stages experience hyposalinities and variable temperature stresses due to freshwater runoff occuring nearshore. Locally, in the Coos Bay estuary salinity values remain relatively constant, at or near 33‰, and would not account for significant larvae mortality. In the adult stages Tasto (1981) demonstrated that egg production was a direct function of ambient temperature. Dungeness crabs from the warmer southern range were found, on the average, to have smaller ovaries and consequently lower reproductive output. Tasto et al (1979) postulated this decrease in egg production due to elevated ambient temperatures as a very strong factor in the Central California crab population decline. Whether the general warming trend since 1957 has affected the Oregon crab population is difficult to access.

The nemertean egg predator, *Carcinonemertes errans*, host specific to *C. magister*, is another hypothesized mechanism driving the crab population fluctuations along the entire West Coast of the United States (Wickham & Fisher 1977, Botsford & Wickham 1978, 1979). There is a high correlation between the number of worms present in an egg clutch and the number of dead eggs. Wickham (1978) estimates that in California an annual loss of more than 50% of *C. magister's* eggs is due to worm feeding. Egg mortality is also caused by worm feeding activities and defecation creating epibiotic fouling by associated blue-green algae, bacteria and protozoans (Fisher 1977, Armstrong & Fisher 1977). Under Wickham's (1979) model in which *C. magister* population levels are drastically fluctuating the worm population is driven to a new high level equilibria. At the new equilibria, *C. errans* exhibits a density-dependent compensatory feeding inhibition which results in depressing worm fecundity in response to a subsequent rise in density levels. The limit on population expansion becomes host availability. The result is a heterogenous distribution, high densities of worms on few crabs. This intensified egg mortality, according to Wickham (1979), pushed the crab population, in the Central California fishery, into long term depressed levels. This model can not account for the coastwide cyclic fluctuations in crab catch since infestation levels are much higher in *C. magister's* southern range. The increased influence of the Davidson Current and the associated warming trend since 1957 may have expanded the distribution of *C. errans* northward (Wickham per.comm.). Increasing densities of *C. errans* in Oregon and Washington suggest this temperature response. However, the impact of *C. errans* on the crabbing industry is difficult to quantify due to the lack of knowledge regarding it's natural history and long term interaction with *C. magister*.

In summary, differences in diurnal and seasonal availability of C. magister larvae in relation to physical parameters has been investigated. My megalopae dispersal theory along with hypothesis have been examined for feasibility in explaining the coast-wide cyclic fluctuations in C. magister's abundance. Analysis indicates a density-independent interaction as the generalized mechanism. Obtainment of the specific causative or contributing factor(s) of what appears to be a natural fluctuation will involve many years of detailed, rigorous research.

RECOMMENDATIONS FOR FURTHER RESEARCH AND REGULATIONS

Detailed studies of the life cycle of C. magister and its relation to oceanographic events have provided us with clues of their specific biological-enviromental interactions. However, further research is necessary to expose the finer details of timing, abundance and dispersal of larvae and the variables influencing both juvenile and adult populations. Clarification of specific details of C. magister's life cycle could justify implementation of management options regarding season, sex restrictions and gear.

A multi-year coastwide serial plankton haul program with simultaneous collection of oceanographic data is necessary in order to statistically support the postulated trends in larvae dynamics. In addition, regular plankton sampling at bay entrances and in nearshore waters would aid in our understanding of the driving mechanism associated with megalopae "swarming" and onshore movement. Counts of individual megalopae attached to the colonial hydriod Vellela vellela could demonstrate the parallelism of year-class strengths that I previously proposed. Stomach analysis of the different larval stages would test several proposed density-dependent mechanisms; food availability, cannabilism and interspecific competition. Other research involving larval dynamics has been suggested by Lough (1976).

The coast-wide impact of the nemertean, Carcinonemertes errans, on C. magister's overall fecundity needs to be thoroughly surveyed by several research teams as is presently being intiated by Wickham (1979). Telemetry tagging of mature female crabs in conjuction with aquistion of the protozoea stage would show migratory behavior and location of hatching sites. Sampling the spermatheca of mature female crabs for signs of sperm prior to fertilization could demonstrate overfishing of mature males, resulting in a lower overall reproductive capacity of the entire population. Unfortunately, there is no preexisting unfished C. magister populations to ultilize as a reference. Therefore, the current situation, natural or not, must be taken as a baseline study. The California Fish and Game, Dungeness Crab Research Program 1974-1981, has provided many suggestions of further research.

There are a few regulations that will help stabilize the crabbing industry. First, moving the starting date of the crabbing season back one month, to January, would reduce the disturbance on females releasing larvae. In addition, the number of recently molted or soft-shelled crabs captured could be substantially reduced. During the megalopae "swarming" period, channel dredging and salmon enhancement should be minimized in order to maximize settlement and stock recruitment.