



Ecological Research Associates

ENVIRONMENTAL SUMMER STUDIES (1982) FOR THE ENDICOTT DEVELOPMENT



VOLUME VI A CONCEPTUAL MODEL: THE MOVEMENT OF JUVENILE ARCTIC CISCO

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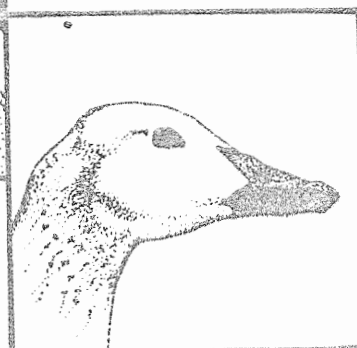
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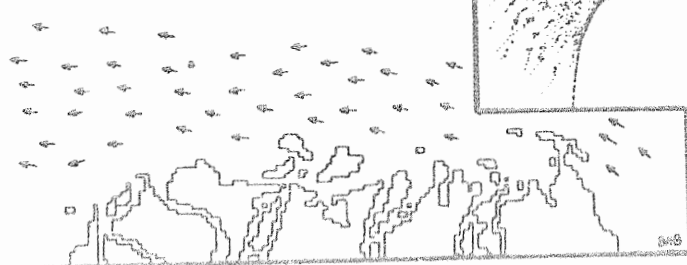
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APRIL 1983

Currents



ENVIRONMENTAL SUMMER STUDIES (1982) FOR THE
ENDICOTT DEVELOPMENT

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Contract No. 82AP35

Editors : B. J. Gallaway, Ph.D.
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April 1983

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GUIDE TO USERS

This report is in six bindings:

Volume I : EXECUTIVE SUMMARY

Volume II : PHYSICAL PROCESSES

Volume III: FISH ECOLOGY

Volume IV : TERRESTRIAL ECOLOGY

Volume V : OCEANOGRAPHIC MODELING

Volume VI : FISH MODELING

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Volume VI : FISH MODELING

PREFACE

Recent exploratory drilling activities in the nearshore waters offshore of the Sagavanirktok River Delta, have resulted in the discovery of potentially commercial quantities of hydrocarbon resources. A group of nine companies owning interests in these hydrocarbon resources, designated as the Endicott Reservoir, have combined their efforts to develop an environmental and geotechnical data base. This data base will be used in support of their economic assessment and environmental permitting related to this development. Based on conceptual engineering studies, the project, to be designated as the Endicott Development, is described in the following paragraphs.

At present it is anticipated that four offshore gravel islands and associated causeway(s), would be constructed as part of this development (Fig. 1). One island would support production and some drilling activities (Production Island B, PIB); two are to be used as satellite drilling islands (SIA, SIC) and one would serve as a waterflood island (WID). These islands would be interconnected by pipelines buried either in subsea trenches, or in causeways. Presently, two transportation routes for moving produced hydrocarbons from PIB to onshore facilities are being evaluated: the "West Dock Pipeline Route" and the "Sag Delta Route" (see Fig. 1).

The project would require construction of a 260-man Base Operations Camp (BOC) located either on PIB, or onshore near the Main Construction Camp (MCC, see Fig. 1). The MCC, requiring approximately 50 acres, would house 750 people.

Approximately eight million cubic yards (MCY) of gravel would be required to construct the islands, causeways, gravel pads and onshore roads. An additional 6500 MCY would be required if inter-island causeways are incorporated into the design. Several potential gravel sources having estimated reserves in excess of 20 million cubic yards have been identified in the area.

Environmental studies related to the the Endicott Development Project commenced during summer 1981, and were followed by winter and summer investigations in 1982. Results from the 1982 studies are presented in this report. The purpose of the studies was to obtain an environmental and ecological data base which could be used in subsequent studies to assess the environmental impacts of the development, as well as be used for design specification. From the onset of the studies, it was recognized that some of the data needed to fulfill program objectives were available from investigations which have been ongoing in the region since the early 1970's. Therefore, the scope of the site-specific studies were focused towards supplementing the existing data base to the degree necessary to define impacts and achieve an environmentally acceptable design. The effort expended on various study elements was allocated proportional to the resource value, public interest or the degree of understanding presently available with respect to a given renewable resource subject to impact. Studies were directed towards those programs which would yield results directly applicable to impact assessments or design improvements.

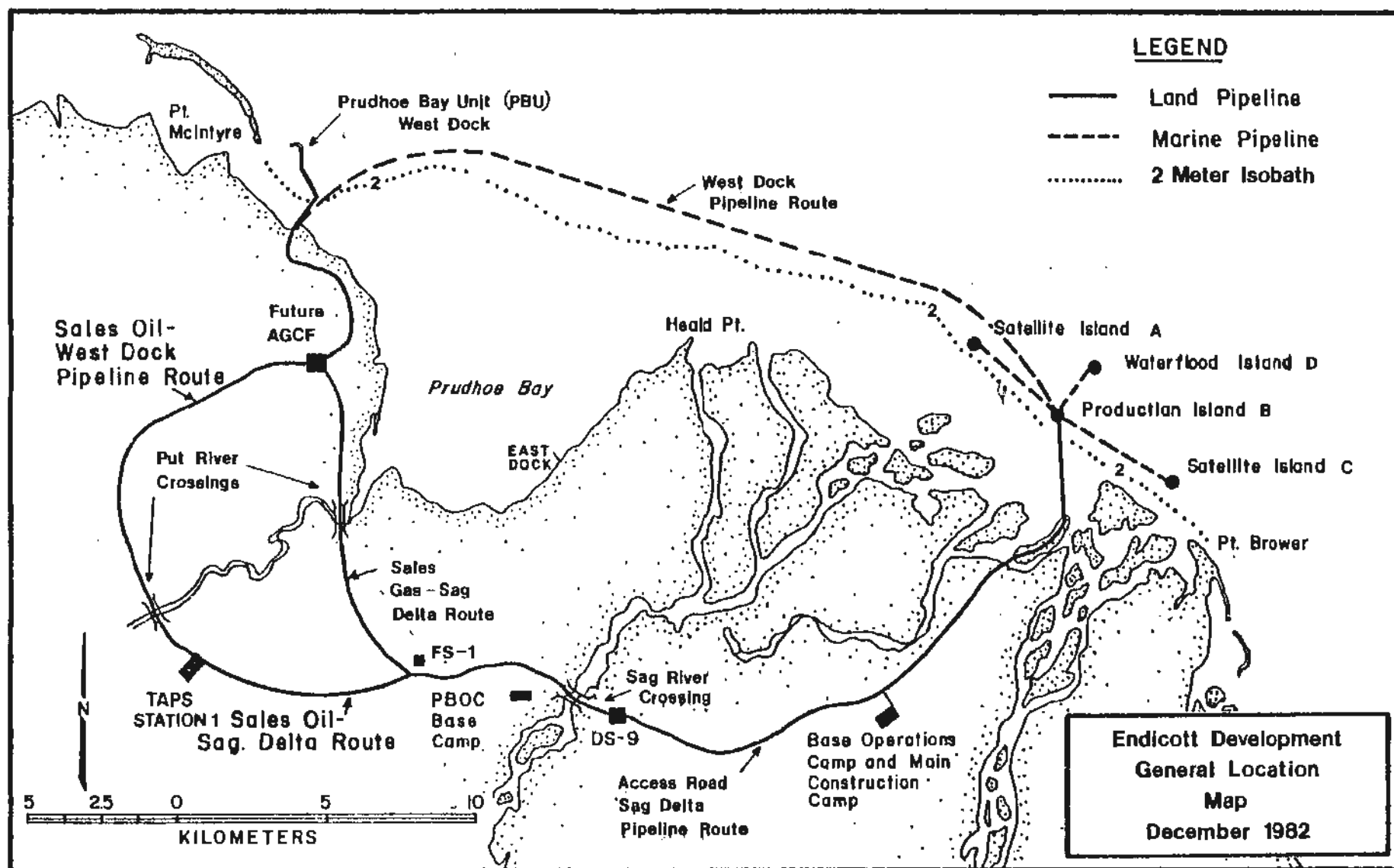
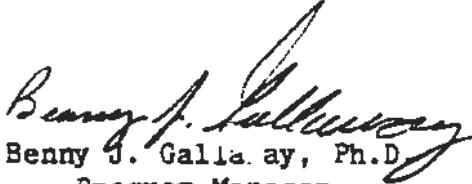


Figure 1. The proposed Endicott Development Project.

Based on these considerations the 1982 summer program placed an emphasis on environmental and oceanographic processes (particularly water quality and sediment transport Volume II) and how these processes regulate anadromous fish utilization of habitats associated with the project area (Volume III). These studies were supplemented by a series of smaller projects: one describing the Howe Island snow goose population and their habitat utilization patterns and productivity; one describing early-season use of the project area by waterfowl; and a final project dedicated to documentation of geobotanical conditions for the proposed road/pipeline corridor through the Sagavanirktok River Delta area. The results of these projects are described in three separate sections of Volume IV.

Prior to its implementation, the 1982 summer study plan was presented to appropriate regulatory agencies. This was supplemented by distribution of the results from previous site-specific studies, allowing agency representatives to make informed comments about the adequacy of the data base, as well as the opportunity to offer suggestions as to how to offset any perceived deficiencies. In general, most reviewers agreed that the major thrust of the program was appropriate, although some believed additional data were needed in specific areas not addressed by the 1982 program. Following a period of discussion about these differences in opinion, the research program was modified to include in the 1982 program some of the suggestions which had been offered by the reviewers. Other suggestions were rejected due to differences in opinion as to the actual need for the data or the timing that such research might best be performed. However, agreement as to what constituted the major issues (water quality, anadromous fish, snow geese, caribou) was reached.

We believe the results of the 1981-82 Endicott Development Project studies when combined with the results of the previous and synoptic investigations performed in the area, will comprise an adequate data and information base for developing a complete environmental assessment for the Project.


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ENVIRONMENTAL SUMMER STUDIES (1982)
FOR THE ENDICOTT DEVELOPMENT

VOLUME VI: A CONCEPTUAL MODEL: THE
MOVEMENT OF JUVENILE ARCTIC CISCO

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April 1983

ACKNOWLEDGEMENTS

The authors acknowledge Sohio Alaska Petroleum Company for enabling the use of a simulation approach in evaluating impact judgements concerning the effects of altered water quality on juvenile Arctic cisco movements and distribution. We also thank NORTEC for their responsiveness in providing the physical simulations upon which the cisco models are based. Lastly, we particularly thank Dr. William H. Neill for his critical review of the draft report.

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1.0 INTRODUCTION

In Volume III of this report, results are presented which suggest a correlation between the abundance of some key anadromous fish and environmental variables which will be locally altered by the presence of the proposed causeway--namely, temperature, salinity and currents. For several years, a major issue of concern has been whether causeway-induced alterations in water quality result in pronounced changes in fish movement and habitat utilization patterns and, if so, to what degree? These concerns are based, to some extent, on the assumption that key species of anadromous fishes have a preference for (or dependence on) relatively warm, low-salinity water during the period they use the nearshore Beaufort Sea. The assumption is largely based on the historical observations that most of the species appear represented in higher densities in waters having these characteristics than in cold, marine waters (e.g. see Craig and Haldorson 1981). While this generalization appears to be true, great variability in both abundance and environmental conditions are commonplace and most studies, like this one, have found only weak (if any) correlation between abundance and environmental conditions. However, the only regional species which has been tested in the laboratory, small Arctic cisco, exhibited a marked preference for warm over cold water.

Recently, most of the concern has been about the effects on small fish since large fish marked on different sides of an existing causeway have been demonstrated to return to overwintering grounds in the same proportion (e.g. Craig and Griffiths 1981, Griffiths and Gallaway 1982). The potential effects on small fish have not been successfully measured by field studies, but have been simulated for the Waterflood Causeway Area (Neill et al. 1983). These simulations treated small Arctic cisco movement and resultant changes in density as a donor-controlled drift process biased by experimentally-determined temperature preferences of the fish. The model used was similar to a previous model which had been described by Balchen (1979). As might have been expected, since density of

fish apparently coming into the system drove the model, the model performed well based upon comparison of predicted to observed catches. Listed below are some of the conclusions related to the Prudhoe Bay Unit Waterflood Causeway (Neill et al. 1983).

- (1) The environmentally-directed simulations performed better than un-directed or reverse-directed versions of the model due to its provision for appropriate responses of small Arctic cisco to temperature/salinity heterogeneity;
- (2) Causeway-induced changes in salinity/temperature regimes resulted in an estimated 7% reduction in the density of small Arctic cisco that would have used the affected area in the absence of the causeway;
- (3) Temperature/salinity heterogeneity forced movement of small Arctic cisco through the breach in a pulsed fashion.
- (4) Under some conditions, movement of small Arctic cisco through the breach and around the end of the causeway were in opposite directions combining to form a gyre; and
- (5) A substantial part of the fluctuations in catch resulted more from environmentally-related changes in catchability than to fluctuations in actual fish density.

Whereas the above model has not been tested against an independent data set, results of this year's monitoring program at the Waterflood Causeway should help to validate (or invalidate) the projections Neill et al. (1983) made based upon the 1982 catch and experimental data.

Development of a more mechanistic model that would stochastically simulate movement of small Arctic cisco as a biased random walk following Saila and Shappy (1963), DeAngelis (1978) and Neill (1979), was considered by Neill et al. (1983) but rejected for several reasons. The primary reason, however, was because such models demand a much higher resolution of environmental conditions than was available for the Waterflood Causeway

area during 1982. The 1982 Summer Studies in the Sagavanirktok River Delta area were designed to provide the necessary resolution of environment, thus enabling the development of a more mechanistic model for small Arctic cisco.

The model described herein was specifically aimed at simulating the summer distributional movements of juvenile Arctic cisco in the vicinity of the Sagavanirktok River Delta. It is based on probabilistic responses of this species to such environmental variables as temperature, salinity and current. The decision to focus solely on juvenile Arctic cisco had three bases. First, Arctic cisco are often the most abundant anadromous species occurring along the Beaufort Sea coast between the Sagavanirktok and Colville rivers during the summer (Bendock 1979, Craig and Haldorson 1980, Griffiths and Gallaway 1982, this report) thus offering an adequate data base from which to compare actual versus simulated fyke net catch trends. Second, a previous study (Fechhelm et al. 1983) had experimentally dealt with juvenile Arctic cisco's physiological and behavioral responses to temperature and salinity--characteristics which formed the principle biological component of our model. Finally, this species seemed an appropriate subject for study since it plays an important role in northern Alaska's commercial and subsistence fisheries.

The success of the simulation efforts were dependent upon having reasonably accurate, fine-scale descriptions of environmental dynamics in and around the Sagavanirktok River Delta over a continuous time period. Although LGL measured some hydrological conditions at specific points on a daily basis as part of our biological sampling responsibility, such data were not adequate for describing the dynamics of temperature and salinity regimes over time and space and we did not measure prevailing currents. Therefore, the development of a physical systems model of nearshore coastal waters was delegated to Northern Technical Services (NORTEC). Their physical model, which generated fine-scale spatial profile of temperature, salinity and current over a continuous 20-day period (9 to 28 July), defined the hydrographic characteristics under which the fish simulations were based.

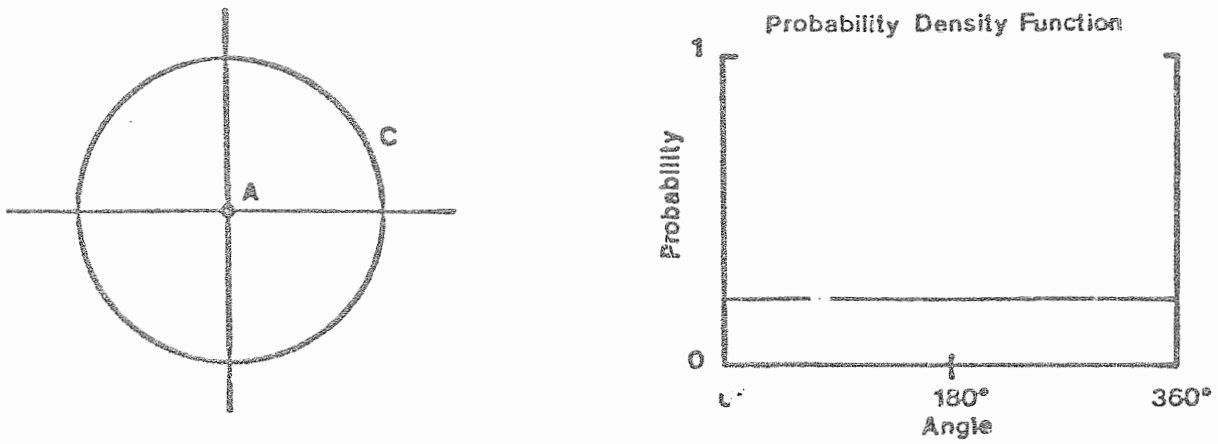
The primary purpose of the fish modeling effort was to develop a method for objectively evaluating subjective opinions regarding the potential impact on Arctic cisco movement resulting from altered water quality regimes. The only basis for an evaluation of the model is whether it successfully mimicked relative changes in the observed, daily fyke net catches. If successful in this regard, and given no evidence to the contrary, the mechanisms which drive the model may indeed represent the mechanisms which influenced short-term Arctic cisco distribution. However, it is important to recognize, regardless of the results described herein, that the model has not been truly tested against an independent data set.

1.1 Biased Random Walk Model: Theory and Structure

Our mechanistic model for stochastically simulating fish movement as a biased, random walk is based upon the works of Salla and Shappy (1963), DeAngelis (1978) and Neill (1979). Under the model, fish in a two-dimensional system are permitted to move in any direction--however, greater weight is given to movement when it is in the direction of an improving environment. This basic concept is represented graphically in Fig. 1.1-1(A). When environmental conditions are homogeneous or heterogeneous but optimum (non-biasing), a fish has an equal probability of moving in any direction. This event can be simulated by placing a fish at the center (point A) of a circle (C) and randomly choosing an angle based on the probability density function (pdf) of the circle. Since there is equal probability of choosing any angle, the subsequent movement will reflect a totally unbiased random walk.

The biased random walk associated with a heterogeneous (biasing) environment can likewise be viewed in terms of probability [Fig. 1.1-1(B)]. In this case, the starting position of the fish (point A) is considered to be one focus of an ellipse whose major axis is directed either ahead or back along the line on which the fish approached A; the ellipse is directed ahead when the previous step resulted in "improving" environment, backwards when the previous step resulted in "worsening" environment. From the elliptical pdf it is evident that although the fish may move in any direction, the probability is greatest for angles that

A Non-biasing Environmental Conditions



B Biasing Environmental Conditions

Improving Environment

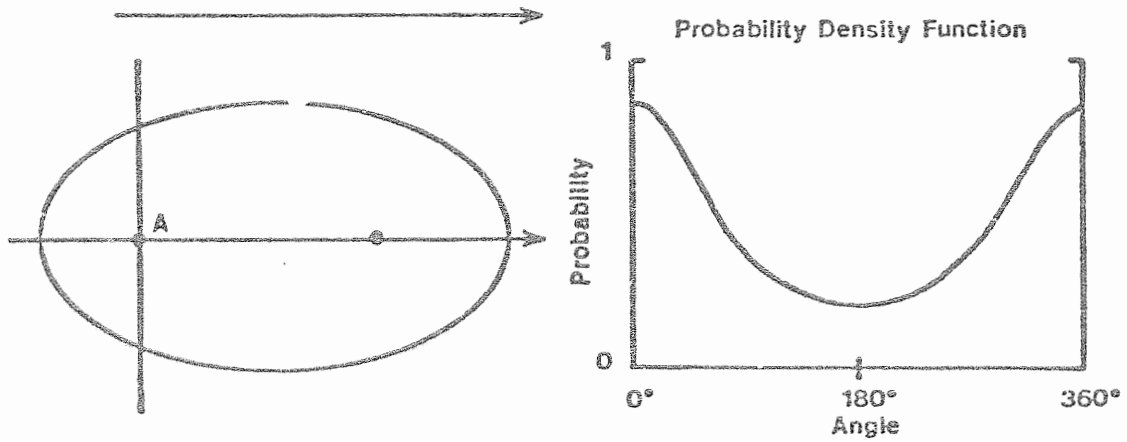


Figure 1.1-1. Probability of change in fish movement under non-biasing (A) and biasing (B) environmental conditions.

direct the fish toward the most "favorable" environment. A model of this sort involves what Neill (1979) has termed "klinokinetic avoidance behavior"--an increase in the probability of changing direction whenever the fish perceives that the environment is deteriorating along its swimming path.

The use of an ellipse and its associated probability density function is a mathematical representation of a "real-world situation" in which fish movement is modified by environmental stimuli. The level of bias instilled by such stimuli can be mathematically conveyed by altering the ellipse's eccentricity (e)--or the degree of elongation of the ellipse (Fig. 1.1-2). Under the homogeneous scenario, a lack of any directional bias is represented by $e=0$ (an ellipse with $e=0$ is in fact a circle). The opposite extreme, in which movement is totally biased, is an ellipse with $e=1$ [see Fig. 1.1-2(A)] or $e=-1$ [see Fig. 1.1-2(D)]; the former in the case of an "improving" environment and the latter in the event of a "worsening" environment. By modifying e between -1 and 1 we have a method for biasing movement with an intensity proportional to the strength of the environmental stimulus.

It was decided to subject our model fish to three environmental variables--current, salinity and temperature. Numerous field studies have demonstrated the latter to be an important factor in controlling the environmental distribution of fish (Fry 1937, Dendy 1948, Hancock 1954, Martin and Baldwin 1958, Horak and Tanner 1964, Brandt et al. 1980). Salinity was not employed specifically as a directive factor in our model; rather, it acted to modify the responses of fish to thermal variability (Garside et al. 1977, Fechtelmann et al. 1983). Temperature thus acted as the primary determinant of random walk bias. Current was used to estimate movement related to passive drift as opposed to thermoregulatory behavior.

A major problem in structuring the model was the unknown relation between the eccentricity associated with a biased random walk and the fish's thermoregulatory behavior. Neill (1979) successfully modeled the distributions of Atlantic salmon (Salmo salar) and carp (Cyprinus carpio) in a one-dimensional system based on the theoretical responses of those species to thermal heterogeneity. The main premise of his model was that successful thermoregulation is a function of two input variables: (1) kind and degree of temperature stress, and (2) recent experience with the

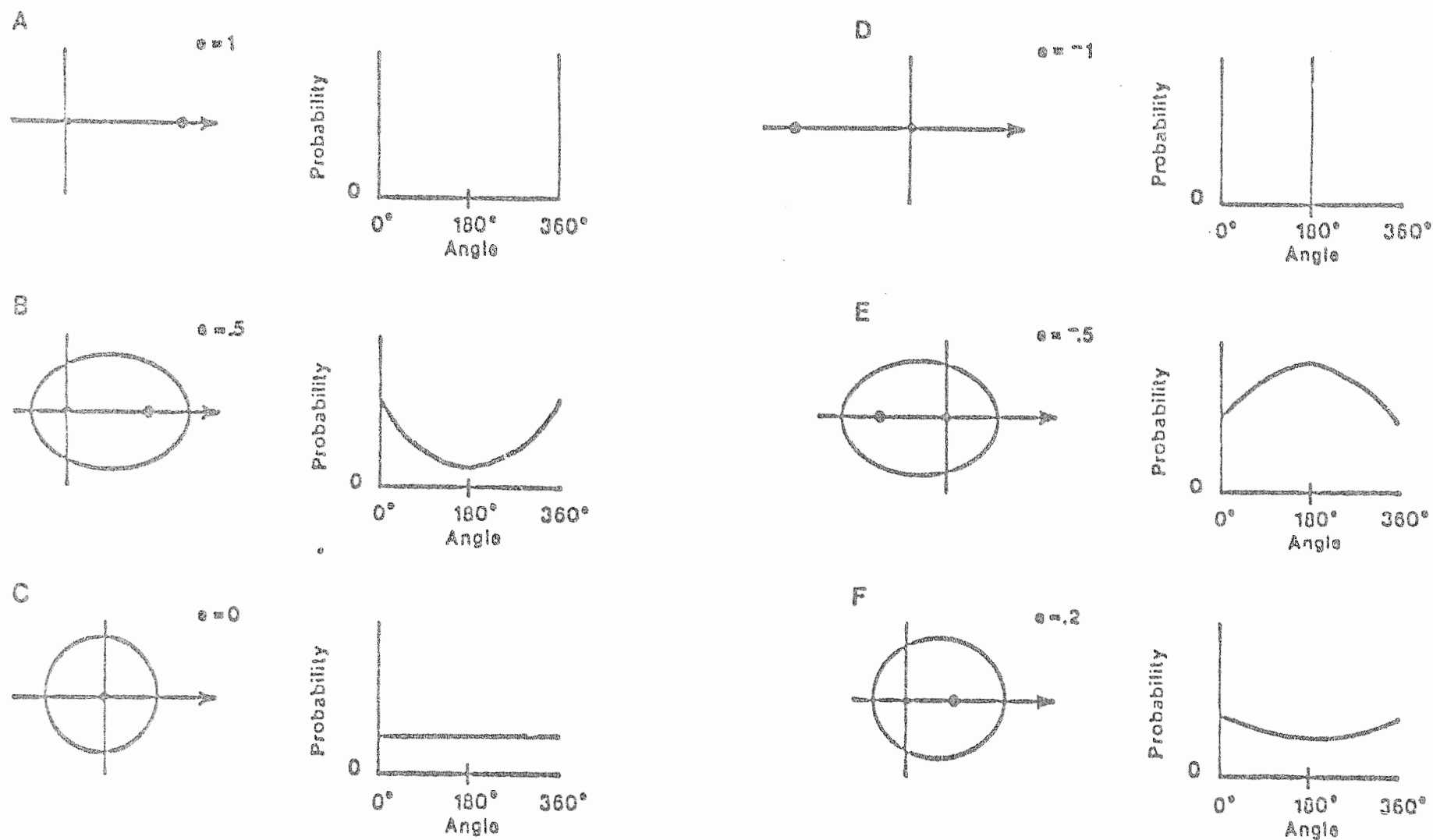


Figure 1.1-2. Probability of various swimming directions based on the probability density of ellipses of varying eccentricity. In each case the fish is assumed to have approached its present position (origin) from the left, and angles are measured as deviations from the direction of the previous step.

rate of environmental temperature change. In other words, the fish must perceive present conditions, and also know whether those conditions are improving or becoming worse.

Like Neill (1979), it was assumed that the kind and degree of temperature stress was a function of the difference between ambient temperature and the fish's preferred temperature. Species-specific thermal preferenda are well-documented (Coutant 1977) and are believed to be thermal levels that allow for optimum physiological and biochemical activity (Fry and Hart 1949, Fisher and Elson 1950, Brett 1967, Jobling 1981). We adopted the following modification of Neill's (1979) thermal stress submodel:

$$\text{STRESS} = \left(\frac{T_a - T_p}{T_{UL} - T_p} \right)^3 \quad \text{if } T_a > T_p \quad (1)$$

and

$$\text{STRESS} = \left(\frac{T_a - T_p}{T_{LL} - T_p} \right)^3 \quad \text{if } T_a < T_p \quad (2)$$

where

- T_a = ambient temperature
- T_p = preferred temperature
- T_{UL} = upper lethal temperature (21°C)
- T_{LL} = lower lethal temperature (0°C)

The lethal temperatures represent the thermal range within which Arctic cisco can survive. The lower limit is obvious given the known environmental conditions of the Beaufort Sea. An upper limit of 21°C was estimated based upon the relationship of preferred to lethal temperature known for several salmonid species and the known preferred temperatures of Arctic cisco (Fechhelm et al. 1983).

The actual values of T_p used for simulations were calculated from juvenile Arctic cisco temperature preference studies (Fechhelm et al. 1983, Fig. 1.1-3). Four different equations were employed depending on ambient conditions:

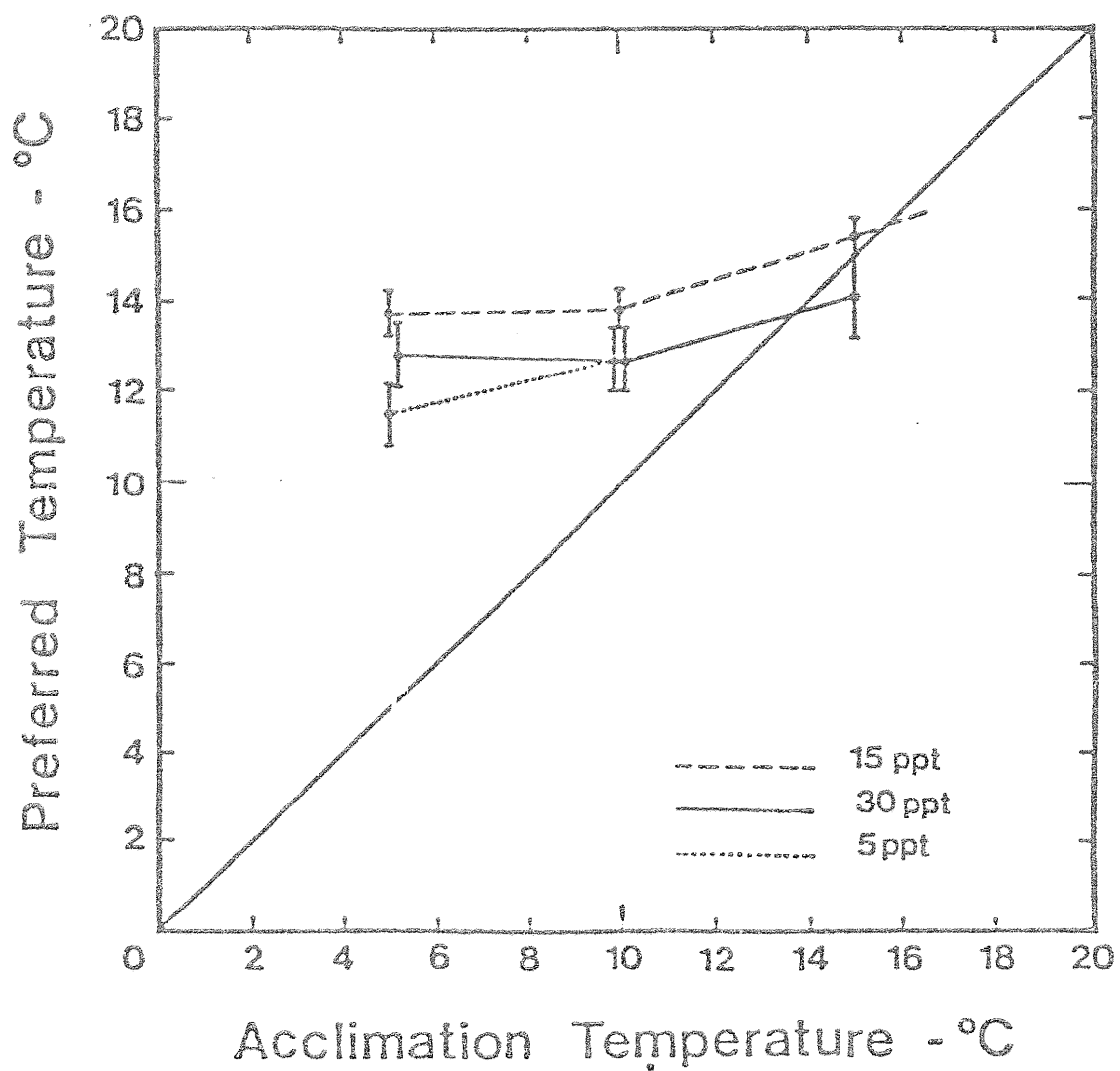


Figure 1.1-3. Temperature preference of the Arctic cisco (From Fechhelm et al. 1983).

$$T_p = 11.5 - (0.06 \cdot S) + (0.3 \cdot T_a) \text{ if } T_a \geq 15 \text{ and } S > 15 \quad (3)$$

$$T_p = 9.25 - (0.09 \cdot S) + (0.3 \cdot T_a) \text{ if } T_a \geq 15 \text{ and } S < 15 \quad (4)$$

$$T_p = 14.7 - (0.067 \cdot S) \text{ if } T_a < 15 \text{ and } S > 15 \quad (5)$$

$$T_p = 12.2 + (0.15 \cdot S) \text{ if } T_a < 15 \text{ and } S < 15 \quad (6)$$

where S is salinity in parts per thousand (ppt). The model thus calculated T_p after every step for each individual fish as a function of temperature and salinity, and in turn compared this preference with T_a to determine stress.

Spatial change in environmental temperature (T_x) was handled in simplistic fashion:

$$T_x = (T_a(t-1) - T_a(t)) / |T_a(t-1) - T_a(t)| \quad (7)$$

Thus T_x had the value 1 for cooling or -1 for warming. Stress and T_x were combined to yield eccentricity:

$$e = a \cdot T_x(\text{Stress}) \quad (8)$$

where a is a constant. Eccentricity was permitted a maximum value of 0.95 so that even under conditions of maximum bias the fish still had a finite probability of making an incorrect choice in its next direction of movement. We can evaluate the logic of equation (8) by assuming a hypothetical sequence of movements in two-dimensional space. A fish in water that is too warm ($T_a > T_p$) completes an incremental step into still warmer water. From equations (1) and (7), Stress will have a positive value, while T_x will be negative. The result is a negative eccentricity which causes the next step to be biased in the opposite direction. Assume the same value of water temperature, but that the fish is moving down the thermal gradient--the values of both Stress and T_x are positive, resulting in a positive eccentricity which favors a continuation of movement in the same direction. Under both scenarios the fish has the highest probability of making the correct choice. The same argument is valid in cold water ($T_a < T_p$).

1.2 The Computer Model

The simulation model was coded and executed on a Hewlett-Packard (HP) 9845 micro-computer. The waters in and around the Sagavanirktok River Delta (Fig. 1.2-1) were represented as a two-dimensional x-y coordinate system within which fish were permitted to freely move (Fig. 1.2-2). Four areas within the system were designated as catch zones and were positioned to correspond with the location of LGL's four nearshore fyke nets. The actual area sampled by the model is indicated by the size of the darkened squares in Fig. 1.2-2. Fish moving into any of these zones were considered "caught" and appropriately recorded as part of that fyke net's daily catch. Our goal was to generate daily catches that could be compared to those actually recorded in the field during 9 to 28 July. Because of restrictions in program execution time, it was quickly evident that it would be impossible to duplicate the actual numbers of fish caught. Such an effort would require simulating numbers of model fish corresponding with the actual Delta population size of small Arctic cisco (likely in excess of 1,000,000). We decided to simulate relative abundance patterns over the 20-day period instead of actual numbers as a matter of practicality.

To initiate the program, 200 fish were randomly positioned in the simulation area. This population size was sufficient enough to generate meaningful daily catches without overtaxing computer time constraints--one hour of computer time was required to simulate the movement of 100 fish per 24 hours. Since preliminary computer runs indicated that fish gravitated rapidly toward shore during the first few days, the initial random distribution was limited to the shoreward 40% of the simulation area. We do not believe this compromised the model because fish could still move offshore if so inclined. The major advantage was that simulated fish distribution reached apparent stability with environmental conditions in about 24-36 h as opposed to the three to four days it would have taken had fish initially been distributed throughout the entire simulation area. Rapid time to stability was important given that the test period was only 20 days long.

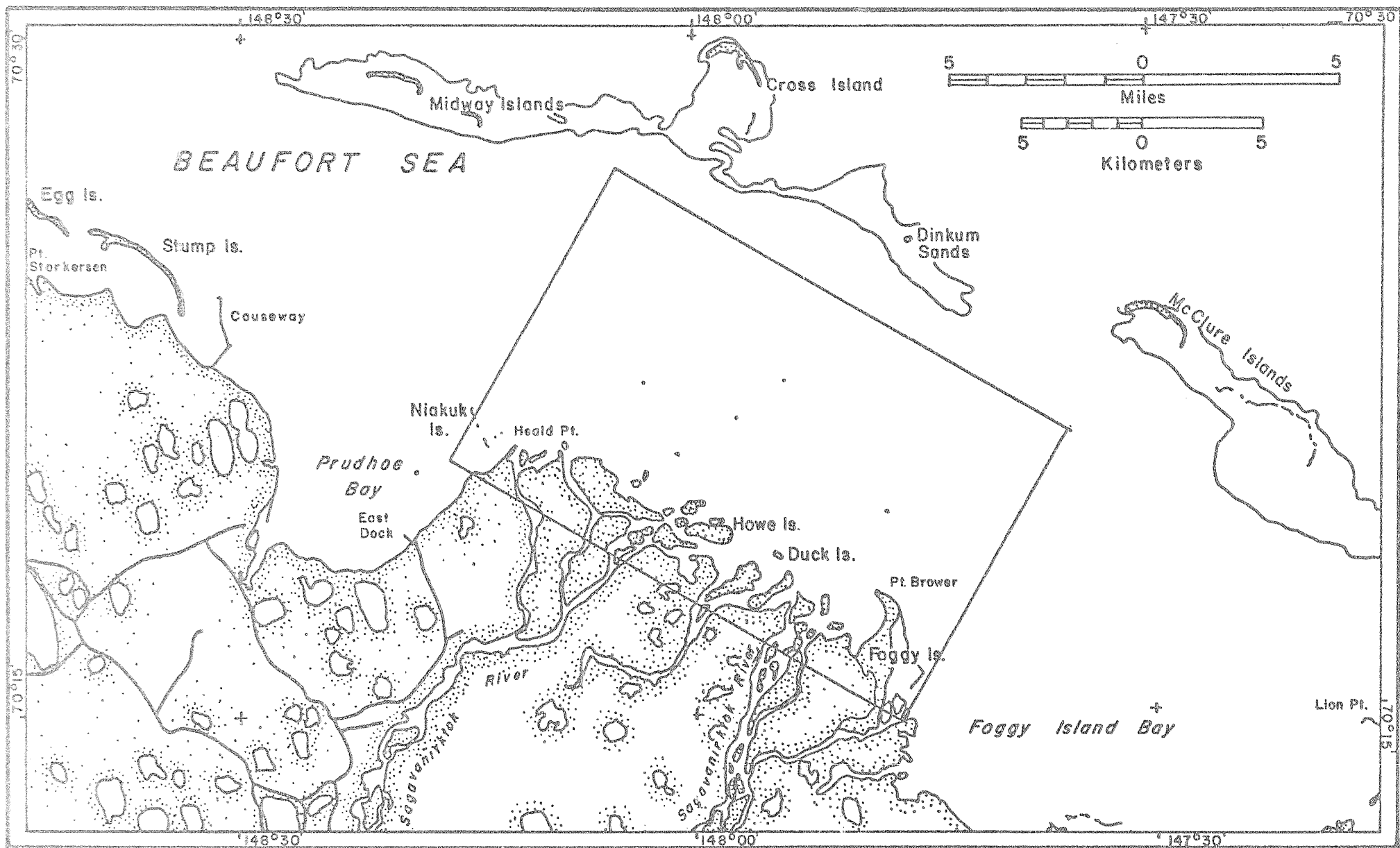


Figure 1.2-1. Simulation area for fish model.

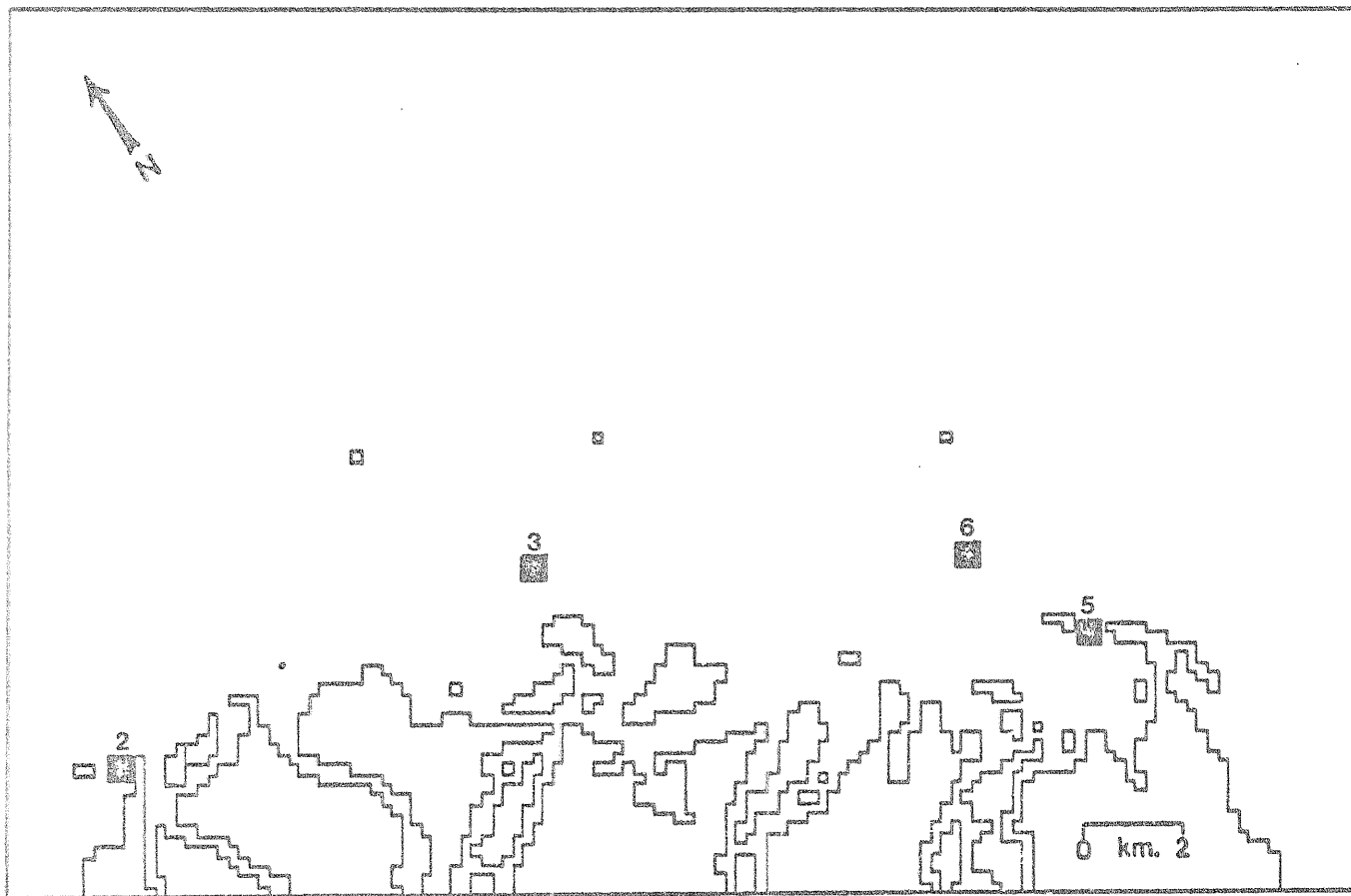


Figure 1.2-2. Digital computer map of Sagavanirktok River Delta. Blackened areas indicate catch zones and correspond to the location of LGL's fyke net stations.

Movement was partitioned into step lengths of one hour. At each step, the position of an individual fish was compared to the existing values of environmental temperature, salinity and current as defined by NORTEC's physical model. These data enabled calculation of the direction of movement for the next step under the biased random walk submodel. The magnitude of the impending step was determined as a function of swimming speed in fish lengths/sec (BLS). BLS (all simulated fish were 150 mm long) was related to temperature (T_a) by the function:

$$BLS = 0.06 \cdot \exp(0.2 \cdot T_a) \quad (9)$$

based on the laboratory experiments on the species by Fechhelm et al. (1983).

Swimming speed in BLS was converted to absolute speed in m/s and scaled to accommodate the model's coordinate system.

Additional thermal bias was instilled by modifying swimming speed as a function of eccentricity. Under unbiased conditions, one might expect a fish's actual swimming path to be more circuitous than under a more directive set of circumstances. By this we mean that as the directive effect of stimuli increases bias (eccentricity), fish are apt to swim an increasingly more direct route. In keeping with this assumption, swimming speed and thus the distance traveled per hour was biased by multiplying it by a fraction of the maximum distance the fish would have traveled had it moved in a straight path.

$$BLS' = BLS \cdot 0.5 (1 - e^2) / (1 - |e| \cos \theta) \quad (10)$$

where: θ is the angle of directed movement.

Fish thus tended to travel a greater distance per unit time when movement was towards more favorable conditions than when movement was little-directed.

Finally, the effect of passive drift due to current was superimposed on the displacement resulting from the fish's swimming action alone. This was accomplished by adding the appropriate current vector to the position the fish would have achieved by swimming, in order to determine the new location from which the fish would begin the next step.

Our model had only two constraints with regard to movement. Fish were not permitted to occupy coordinates corresponding to land mass nor were they allowed to traverse the upper (northeastern) boundary of the system. Fish passing across the northwestern boundary were reinstated on the southeastern boundary at the same y coordinate. Conversely fish moving over the southeastern boundary were repositioned at the northwestern boundary. This procedure ensured a constant number of fish (200) in the simulation system while still enabling them to pass through the modeled area in a net eastward or westward direction, depending on the effects of environmental variables.

We had originally intended to mimic fyke net catches in each of the four field sampling locations. However, the NORTEC environmental model did not specify conditions in the regions of fyke net sampling Stations 2 and 5 along the western and eastern boundaries of the study area, respectively. As a result, our comparisons of model to observed trends were limited to fyke net sampling Stations 3 and 6.

The simulation model was "tuned" by varying estimates of only three of the parameters (whose actual values we had no way of knowing) until goodness-of-fit with the observed catch series at Station 3 was maximized. Such model fitting is no less legitimate than parameterization of a regression model. Had our model's structure been patently wrong, it is unlikely that any combination of three parameter estimates could have produced high correlation between observed and predicted catches. The simulations involved 96,000 (200 fish x 24 h x 20 days) events, each containing a random element.

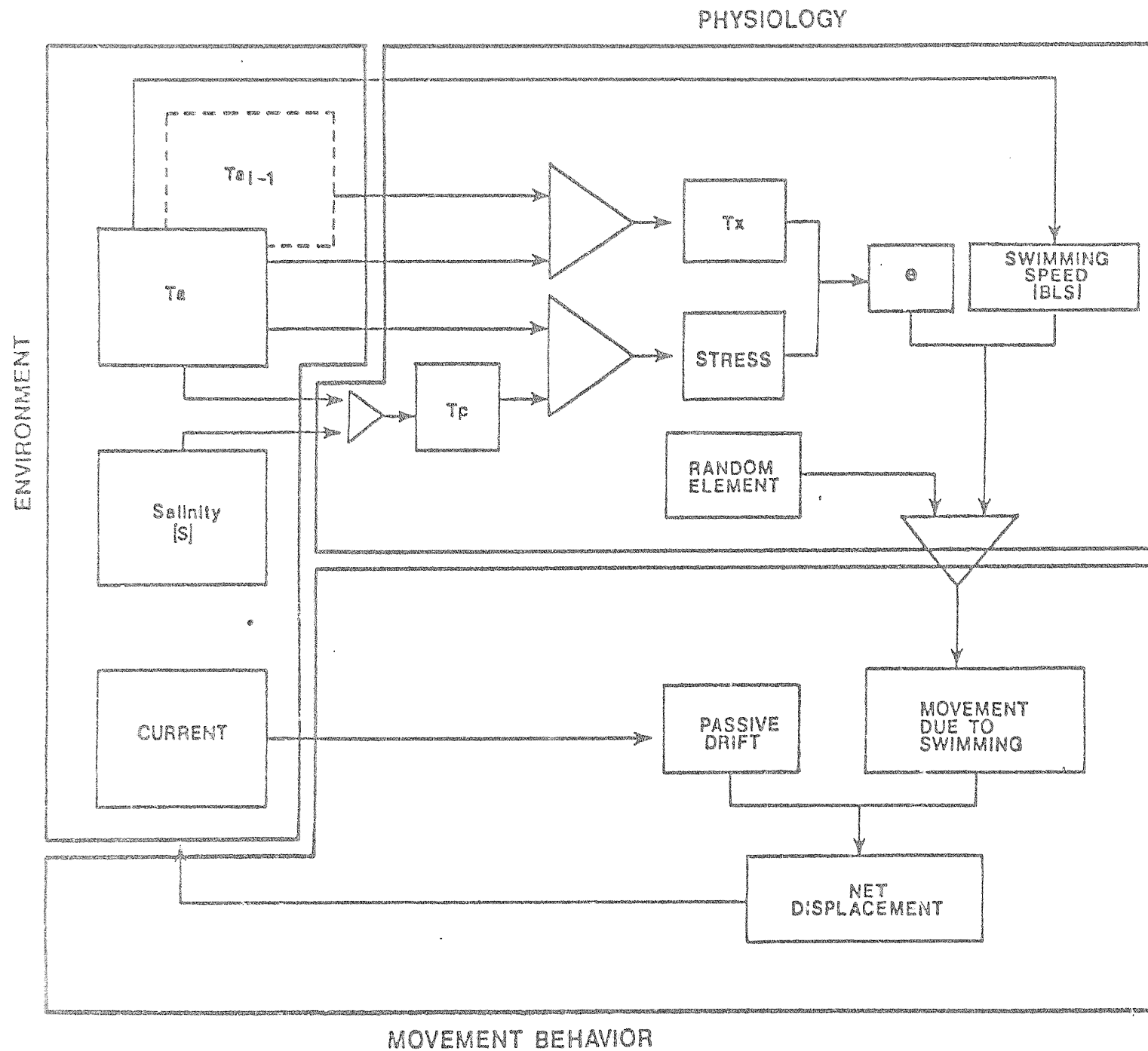
The three parameters which were varied in our model-fitting exercise included coefficient "a" in equation (8), a multiple of the swimming speed computed in equation (10), and a multiple of current speed generated by the NORTEC model. Coefficient "a" represents a measure of juvenile Arctic cisco's thermal sensitivity or "gain", about which there exists no empirical information; we tried values ranging from 5 to 100 in the effort

to fit the model. For swimming speed we tried the multiples of 2, 3, 4 and 5 because we did not believe that the speeds determined in the laboratory were likely to have been as high as those actually occurring in the field. In contrast, different fractional multiples of current speed were tested, the rationale being that fish likely make use of bathymetric features, frictional zones, rheotactic responses, etc. to modify the apparent strength of localized current. Best results were obtained using a value of 50 for coefficient "a", a swimming speed multiple of 2 and a current velocity multiple of 0.4.

Modeled catch trends were compared with field catch trends based on both raw and demodulated data. By the latter we mean that results were subjected to spectral analysis in order to detect and compensate for high frequency oscillations in daily catch during the 20-day simulation period. Once the high frequency component was determined, it was incorporated into a demodulating filter to transform or smooth the data. Such demodulation enables one to compare actual versus simulated catch trends without the confounding effect of high frequency noise. The 20-day simulation time interval turned out to be too short a period in which to detect a major frequency component, therefore the same frequency component that was determined for field data was used in demodulating the model catch series.

1.3 Model Summary

The biased random walk model can be summarized in terms of three components--environment, physiology and movement behavior (Fig. 1.3-1). The difference in ambient environmental temperature at a given position (T_a) from that at the preceding position (T_{ai-1}) define the nature of temperature change (T_x) being experienced by the fish. Preferred temperature (T_p) is determined from salinity (S) and ambient temperature (Fechhelm et al. 1983). Stress, which is defined as a function of the difference between preferred and ambient temperature, combines with T_x to determine the eccentricity (e) or bias in the impending choice of directed movement. Although the subsequent direction of movement stems from eccentricity alone, the magnitude of that directed movement requires input from both eccentricity and the fish's swimming speed. The latter merely scales the ultimate vector emanating from the focus of the ellipse. With



T_a -Ambient Temperature

T_p -Preferred Temperature

T_x -Temperature Change

• - Eccentricity

Figure 1.3-1. Conceptual diagram of the biased random walk fish model.

the stage set, a random number is generated and applied to the probability density function of the ellipse to determine the fish's movement (direction and magnitude).

Collectively, the above steps generate a change of position due solely to the swimming action of the fish. This movement is then augmented by passive drift induced by current. The sum of these two vectors result in the net displacement or movement of the fish. The new position occupied by the fish at this point has a set of environmental conditions and the model thus begins its next iteration.

2.0 RESULTS AND DISCUSSION

Prior to description and discussion of results, the reader is reminded that the model has not been truly tested against an independent data set (Station 6 trends were, however, predicted based on parameters estimated from Station 3 data). The only basis for an evaluation of the model is whether it successfully mimics relative changes in the observed, daily fyke net catches. If successful in this regard and given no evidence to the contrary, the mechanisms which drive the model may indeed represent the mechanisms which influenced short-term Arctic cisco distribution.

2.1 Results

Daily distributions of the 200 model fish are shown by Figs. A-1 through A-19 in the Appendix to this report. Station 3 catch data, predicted and actual, for the period 11 to 28 July are presented graphically in Fig. 2.1-1. Values for model catch have been uniformly scaled so that the maximum corresponds with that of the actual catch series. This manipulation was acceptable since we are interested only in relative trends. The resulting Pearson product moment correlation coefficients of 0.87 for catch per fyke-net hour and 0.97 for demodulated catch per fyke-net hour imply a high degree of similarity between the real and modeled catch trends at sampling Station 3.

Simulated catch at Station 6 showed a poor correlation (catch per fyke-net hour: $r=-0.31$; demodulated catch per fyke net hour: $r=-0.20$) with actual catches (Fig. 2.1-2). The only apparent consistency between the

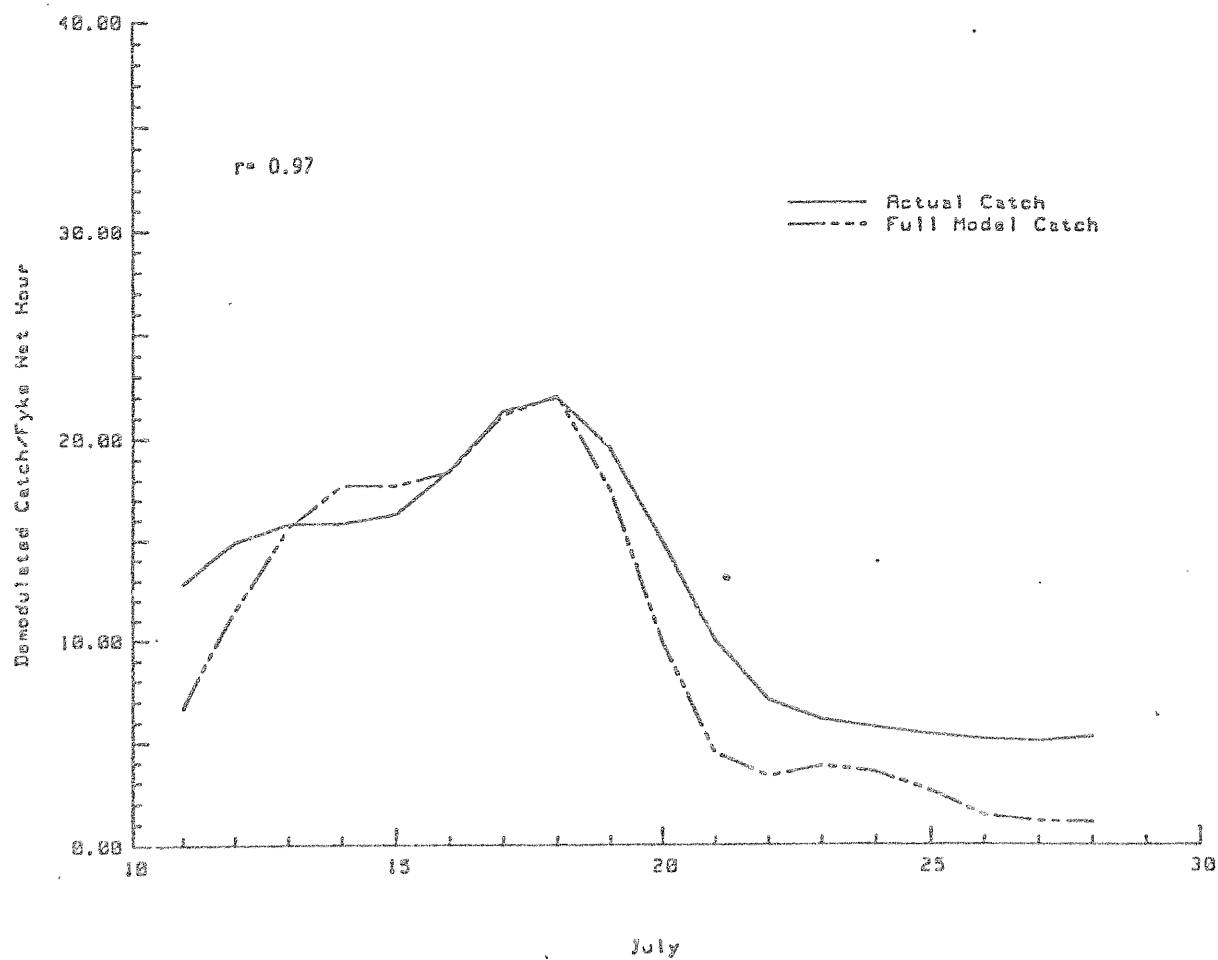
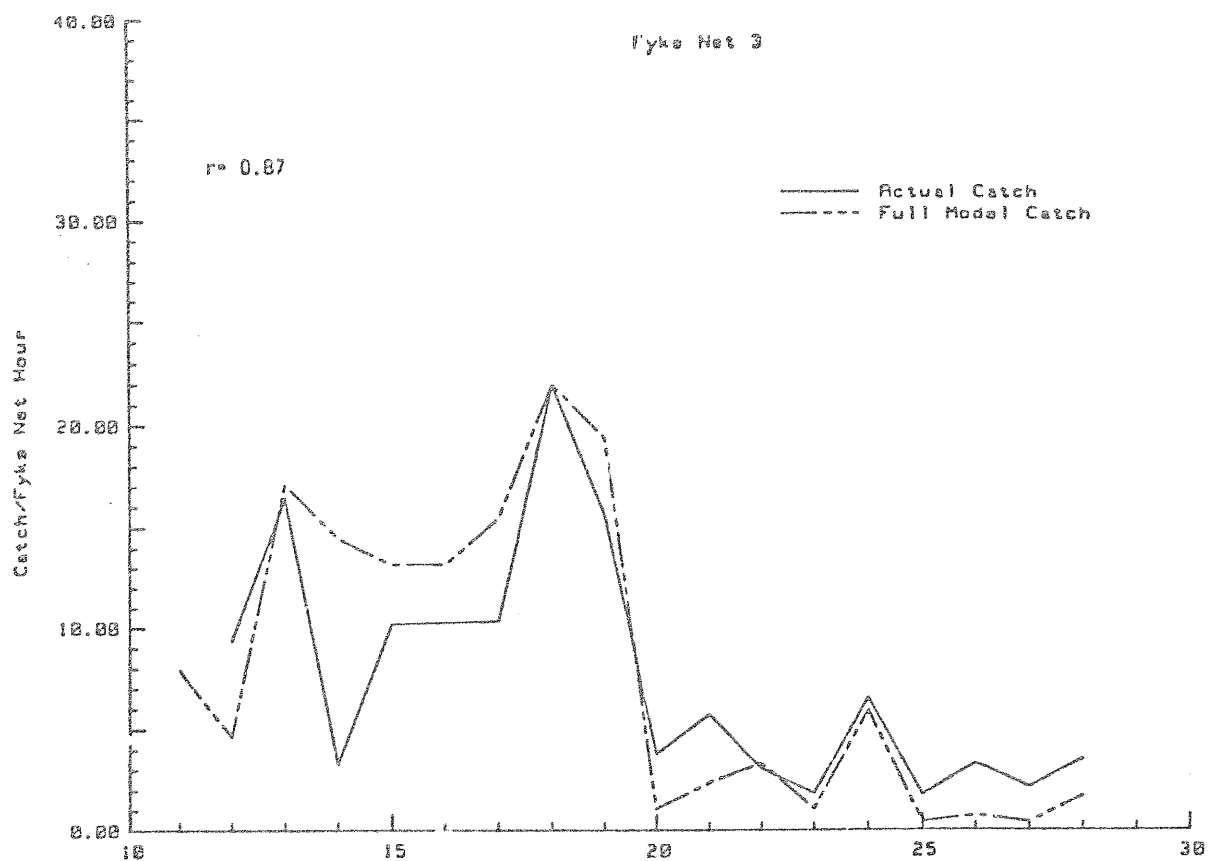


Figure 2.1-1. Actual versus full model catch at Station 3 for the period July 9-July 28.

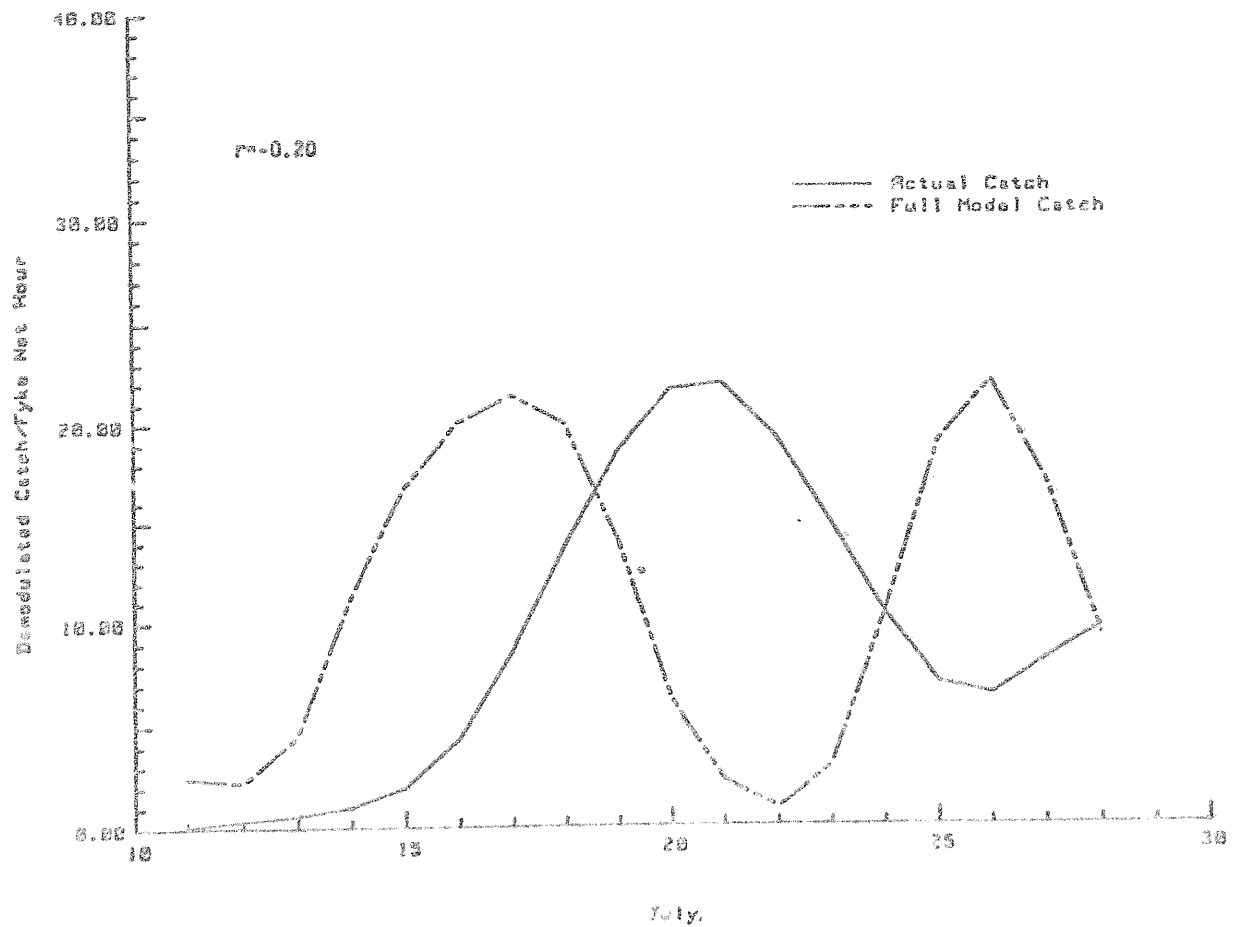
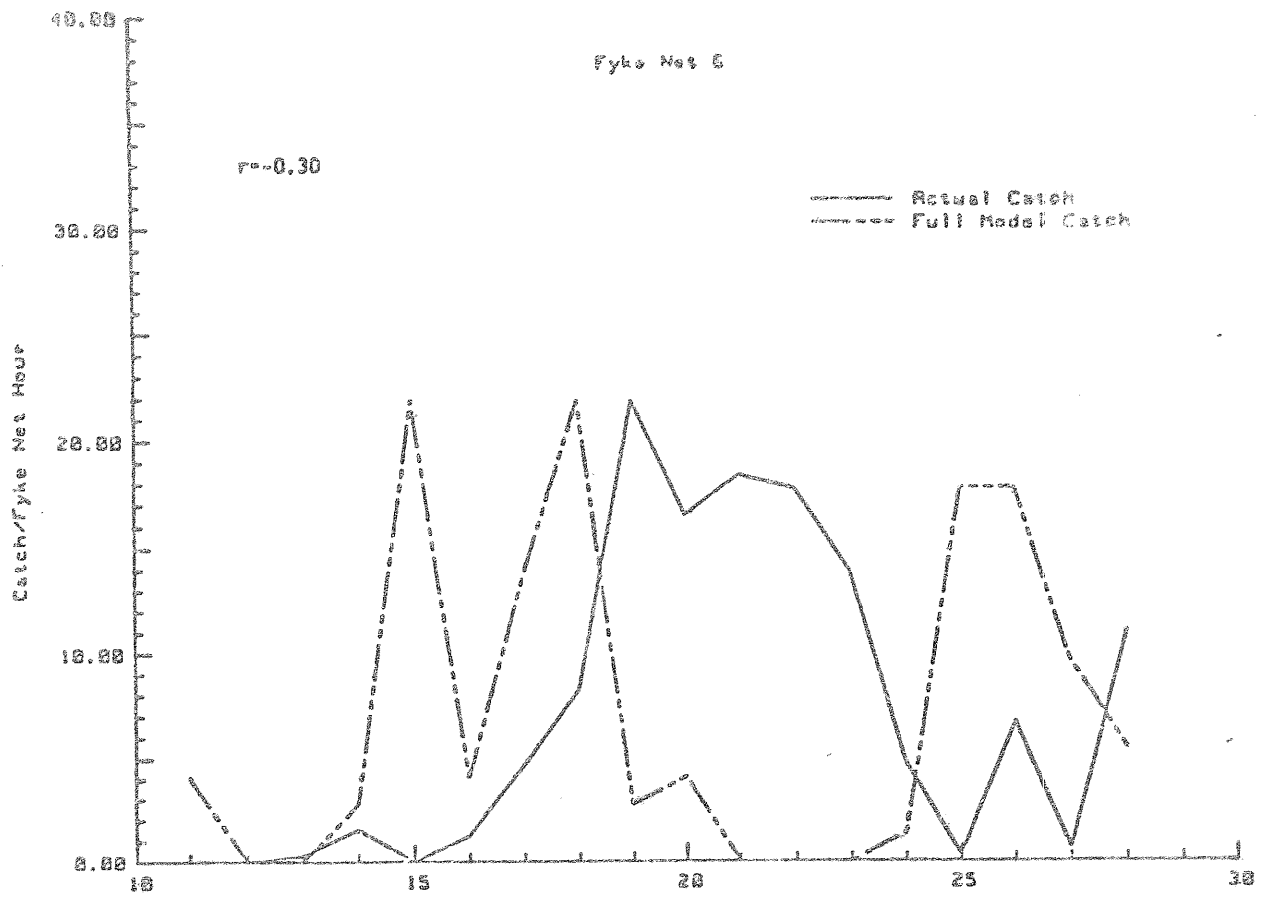


Figure 2.1-2. Actual versus full model catch at Station 6 for the period July 9-July 28.

two series occurred during the first few days when both the actual and predicted catches were virtually non-existent. The first major surge in catch under the modeled scenario occurred on 14 July, while its real-world counterpart did not undergo a substantial increase until 16-17 July.

By its design, the random walk fish model generates rapid changes in thermal bias at about 9.5-10°C. This, in effect, forms a thermal resistance front. According to the physical model, the thermal plume generated by river discharge pushed the 10°C isotherm through the Station 6 area on 14 July (Fig. 2.1-3); about the same time as the initial surge in simulated catch. However, LGL's field temperatures measured at Station 6 did not reach 10°C until 20 July (see Fig. 2.1-3, also note the agreement at Station 3), which was the time that the actual fyke net catch first peaked. This trend prompted us to compare the catch trends at Station 6 after having subjected the simulation data to a phase shift correlation analysis.

In terms of maximum correlation, the observed catch lagged the model's predicted catch by four days (Fig. 2.1-4). This shift improved the correlations to $r=0.30$ and $r=0.70$ for the observed and demodulated series, respectively. Lag-correlation-analysis indicated that the physical model's predicted temperature series lags LGL's recorded temperature series by five days (Fig. 2.1-5). The aberrant situation at Station 6 in no way compromises the physical model's overall validity since there was good agreement between predicted and actual temperatures recorded at Station 3 (see Fig. 2.1-3). Rather, the location of our fyke net at Station 6 turned out to be an unfortunate choice. Station 6 was located in an area in which water conditions undergo a high degree of transition. According to the NORTEC physical model, the region is consistently characterized by abrupt gradients of both temperature and salinity. Throughout the summer sampling period NORTEC's Mooring 4, which is located in the same general vicinity, also documented high frequency fluctuations of both temperature and salinity (Section 7, Volume 2). This instability may reflect a sharp interface between cold, highly saline oceanic water and the relatively warmer, less saline waters that are

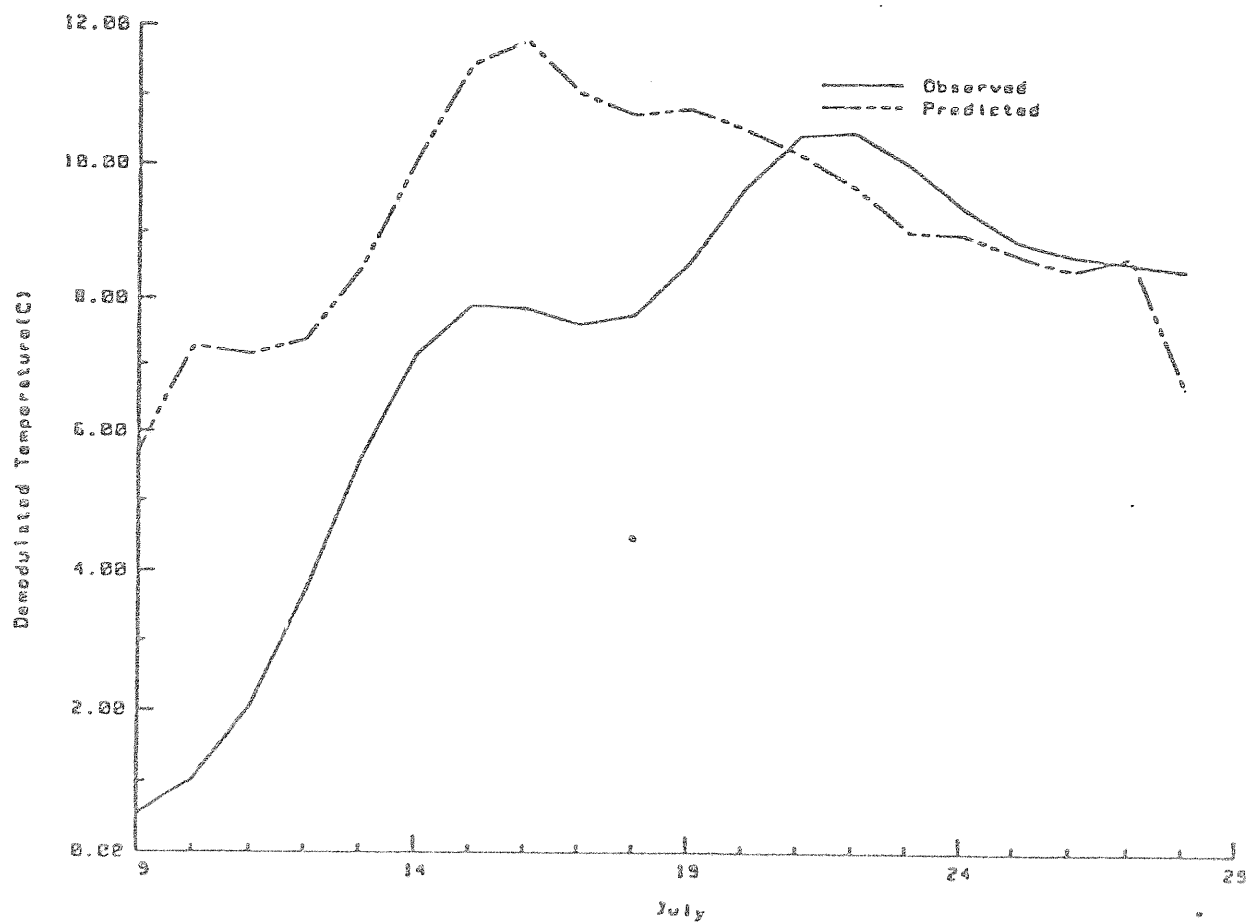
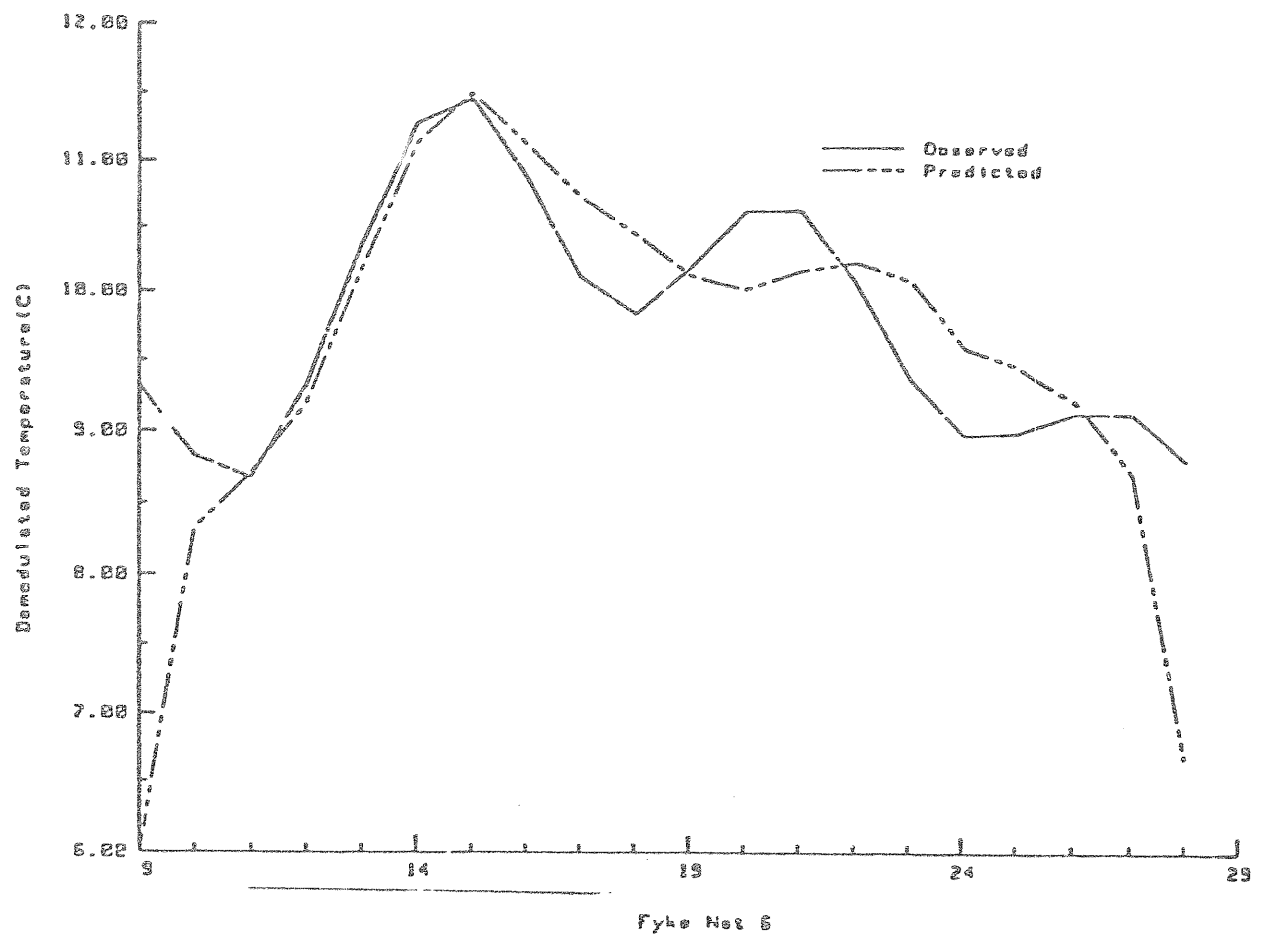


Figure 2.1-3. Observed versus predicted temperatures at Station 3 and 6 for the period July 9-July 28.

Cross Correlation Net 6

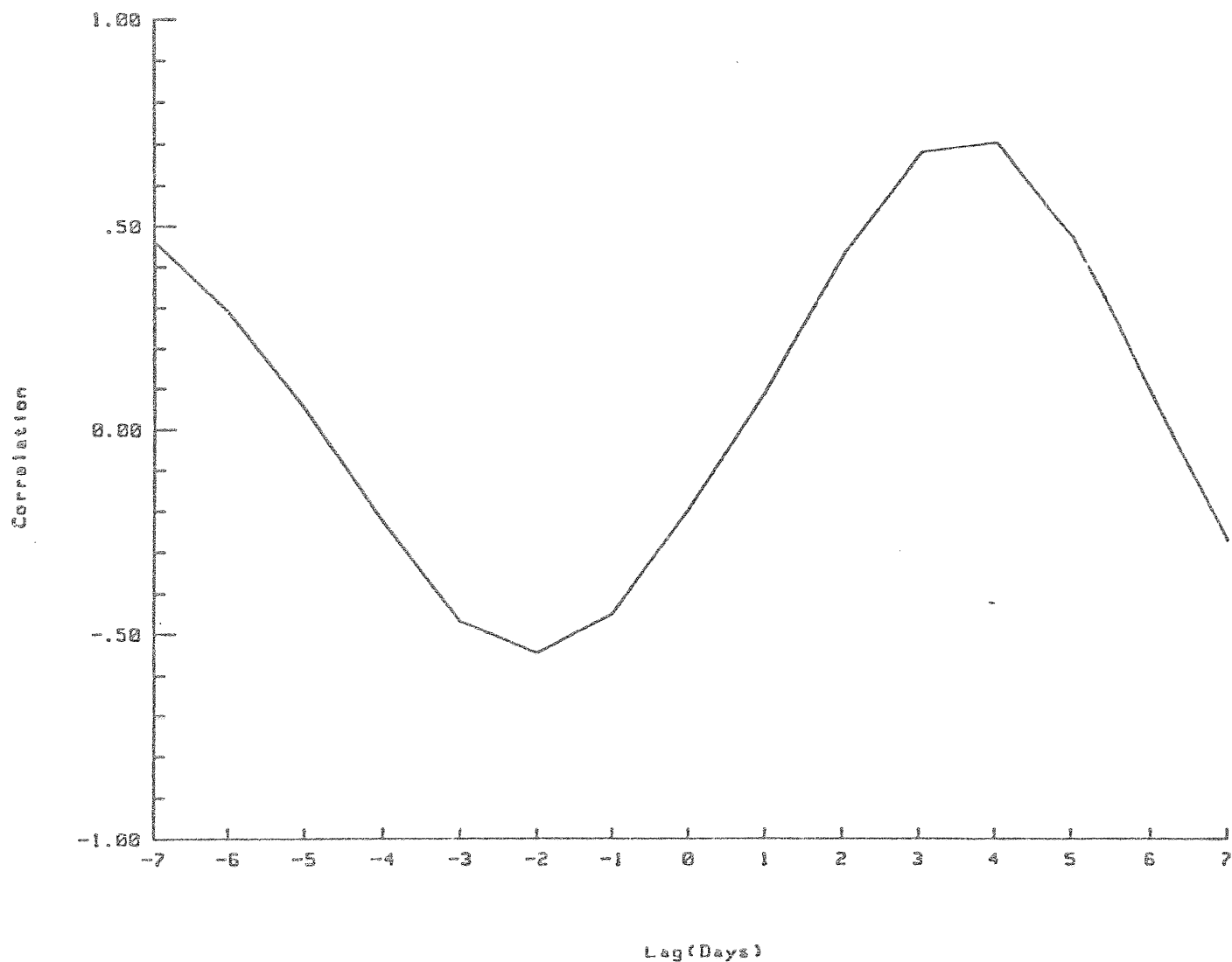


Figure 2.1-4. Plot of correlations between actual (demodulated) and predicted (demodulated) catch at fyke net Station 6 as a function of various phase shift comparisons.

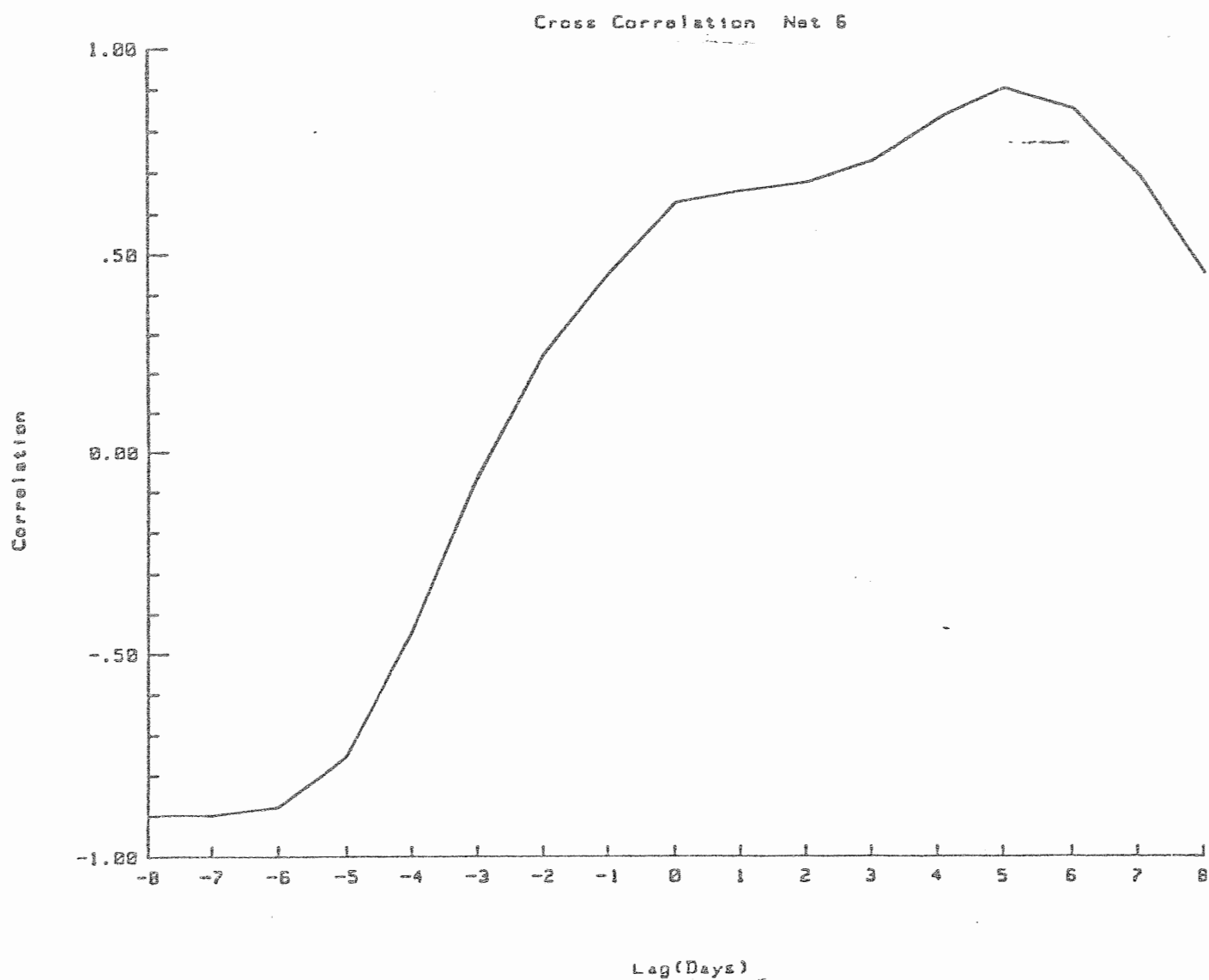


Figure 2.1-5. Plot of correlations between observed (demodulated) and predicted (demodulated) temperatures at fyke net Station 6 as a function of various phase shift comparisons.

typically found around the mouth of the Delta. Such conditions could create localized, short-term discrepancies with respect to physical modeling; which in turn, would distort the reliability of our fish simulation model.

In the simulation, Arctic cisco movement could be segregated into several distinct phases. During the period 9 to 12 July, strong southeasterly currents along with relatively cold offshore water caused the model fish to move in a westerly direction in a narrow band hugging the coast (Appendix Figs. A-1 to A-3). Fish passing around Point Brower (Station 5) were immediately deflected down into the warmer waters of the Delta mouth. Station 6 was effectively by-passed, resulting in a negligible catch. Cisco continued to move across the Delta--passing through the area of Station 3, around Heald Point (Station 2) and on into Prudhoe Bay. The net time required for the model fish to transit the Delta mouth between Point Brower and Heald Point was approximately three to four days.

Weak currents prevailed during 13 to 17 July (Appendix Figs. A-4 through A-8) and caused a cessation of westerly fish movement. The virtual absence of longshore currents enabled a warm-water plume, generated by the Sagavanirktok River, to extend further offshore than was the case earlier. Although fish continued to "mill about" in nearshore areas, there was a gradual seaward dispersion in conjunction with the offshore movement of the 10° thermocline. During this period the warm water plume pushed through the area of Station 6 and the catch increased substantially.

The remaining eleven days (Appendix Figs. A-9 through A-19) were characterized, for the most part, by alternating periods of weak and strong easterly currents. The extended warm water plume was essentially maintained until 22 July which, in addition to the offshore movement of water, scattered fish over a broader area and away from nearshore areas. The period of 23-28 July (Appendix Figs. A-14 through A-19) was characterized by a collapse in the warm-water plume caused, in part, by decreasing river discharge. That fish fail to move closer to shore during this period may be a result of prevailing current patterns. Prominent

southeasterly currents exhibit a slight seaward bias in water movement across the face of the Delta. This net trend may have been sufficient enough to counteract the fishs' thermoregulatory behavior.

In an attempt to isolate the effects of current on Arctic cisco movement, the model was run using a homothermal environment. Temperature was held at a constant 8°C for the sake of determining swimming speed while eccentricity was maintained at 0. Figure 2.1-6 shows the predicted catch under the "current only" model versus observed catch. Under the "current only" scenario, the correlation with demodulated actual catch decreased to $r=0.86$ and $r=-0.50$ for Stations 3 and 6, respectively. It appears that the current-only model did not mimic field data to the extent of the full model, although the correlation at Station 3 suggests that current played the major role in the observed Arctic cisco distribution. Because we might expect the interactive effect of temperature and current to vary, both spatially and temporally, it is difficult to isolate their individual roles in the overall picture of fish movement. The important consideration is that, under the model, both current and temperature appear to direct the daily movements of Arctic cisco in and around the Sagavanirktok River Delta, and that successful interpretation of abundance patterns requires consideration of both factors.

2.2 Discussion

Despite encountering problems, the authors would judge the overall model results as being encouraging. Good model fit occurred at Station 3 where the oceanographic model reliably predicted environmental conditions. At Station 6, where temperature projections were similar but about five days out of phase with measured values, the actual catch series lagged the modeled catch series by four days. Although three model parameters were adjusted in the attempt to establish optimum correlation, it seems highly unlikely that the similarities occurred by random chance, since the results generated are based on 96,000 random events. On this basis, the model appears to have some credibility, and supports the contention that current, and to a lesser extent, temperature likely represent two primary determinants of Arctic cisco distribution in the vicinity of the Sagavanirktok River Delta.

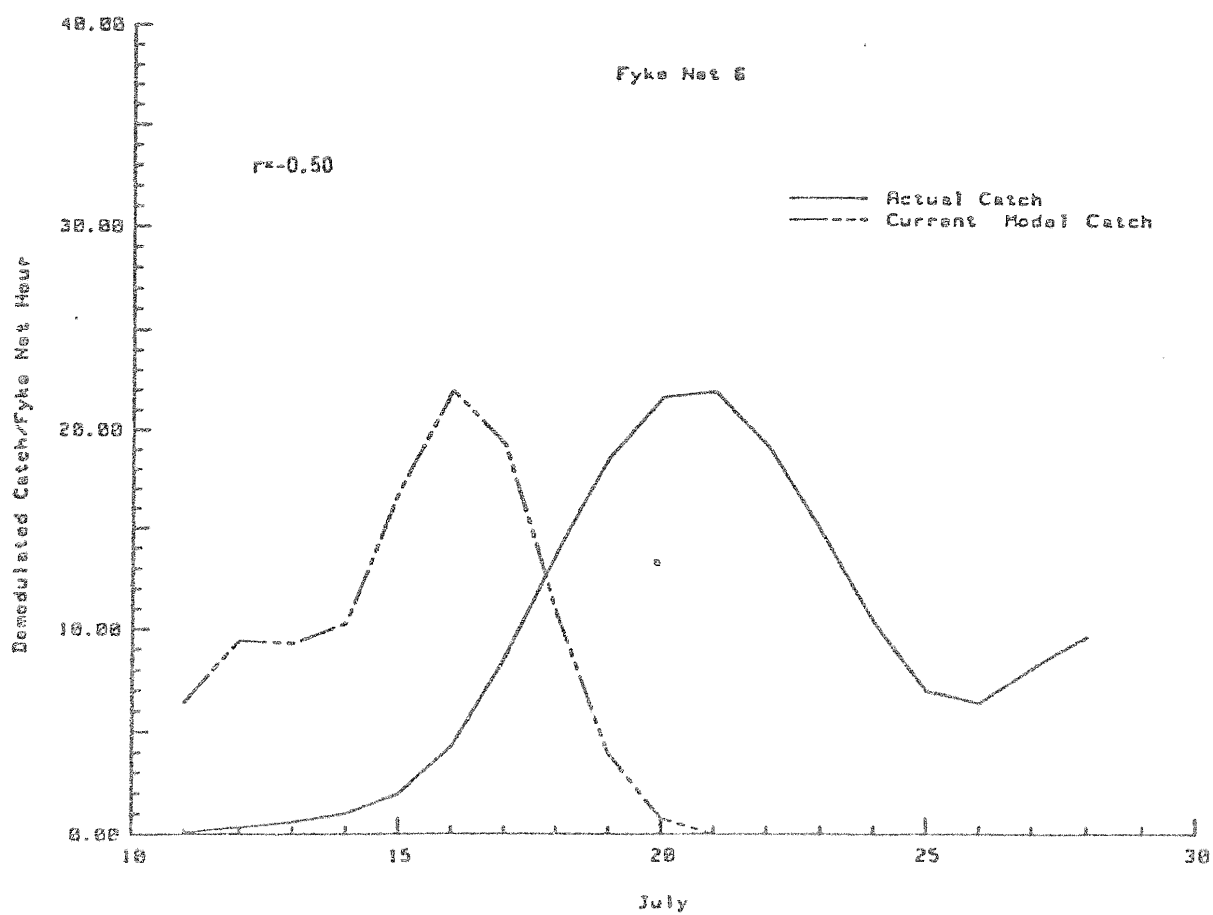
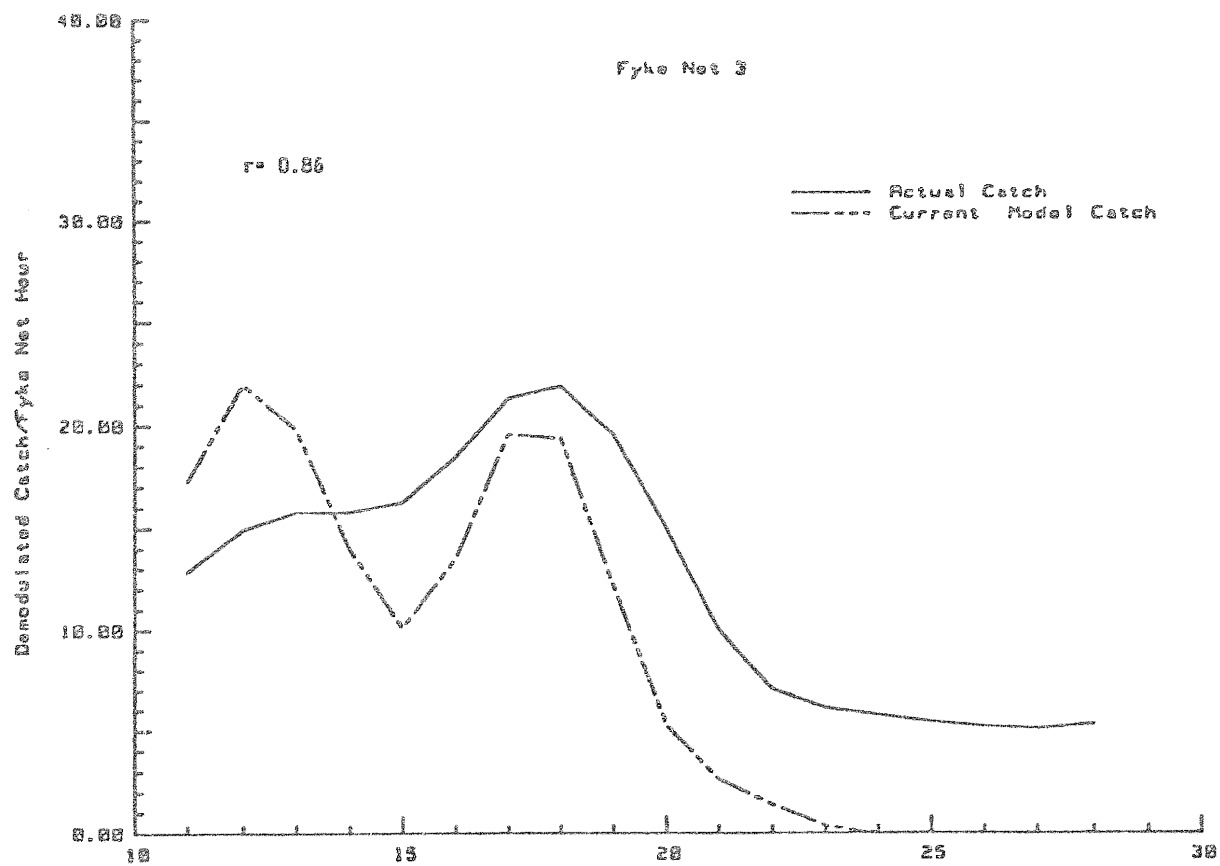


Figure 2.1-6. Actual versus "current only" model catch at Stations 3 and 6 for the period July 9-July 28.

Although random walk theory is not without precedent (i.e. Saila and Shappy 1963, DeAnglis 1978, Neill 1979), our approach represents an initial attempt at integrating a testable mechanistic model with fine-scale environmental data. At this preliminary stage the model has, to some degree, accomplished its initial goal or "passed" the first test given an adequate portrayal of the environment--it reasonably mimics relative changes in the daily fyke net catches of juvenile (150 mm) Arctic cisco.

Statistical modeling could also be used for impact assessment purposes but would take a different approach. Here, rather than compare actual abundance to patterns projected based entirely upon known or expected functional relationships, all the factors which can be included in a stepwise time series multiple regression would be included, until a high percentage of the sample variance was explained. Using auto- as well as cross-correlation approaches it is anticipated that a high degree of the CPUE sample variances at the various Sagavanirktok River Delta sampling stations could be accounted for, or explained from the existing data set. By this we mean that the observed curves could have been fitted as functions of temperature, salinity, currents, previous abundance at a location, abundance at other locations, etc. Once fitted, a series of correlated variables like temperature and salinity could be changed as they would have occurred if a causeway configuration had been present, while holding all the other variable series the same. The output could then be statistically compared to the original observations to obtain an estimate of the effects of the projected causeway-induced changes in water quality on fish abundance patterns.

Neither approach is perfect, but we believe either would be preferable over simple opinion not subjected to any scrutiny for internal consistency. The simulation modeling approach was selected for development in this program because it is free to fail. By this, we mean that simulation modeling was used as a test to determine whether the perceived functional relationships could reasonably account for observed distributions. It was believed that, if the simulations produced some reasonable representation of the observed dynamics, they would provide credence for the data base or statistical modeling approach. That is, it could be more safely assumed that the statistical model for one year will

be like the model for another year, because the observed correlations were more likely attributable to functional responses of the fish to the variables included in the regressions as opposed to some other unmeasured factors. The primary reason for using statistical modeling as opposed to simulation modeling is that once it has been determined that the correlations have a functional basis, the former is less time-consuming and cheaper than simulation modeling. On the other hand, simulation modeling offers the advantage of allowing one to examine places within the geographic bounds of the model system where actual data were not collected.

As noted earlier, the model has yet to be tested against a truly independent data set. In this regard, we caution against over anticipating the model's eventual worth at this time. Many questions remain unanswered and future pitfalls could develop. Nevertheless, the modeling approach could ultimately represent an important and a cost-effective tool for describing the migrational and distributional patterns of coastal fish stocks as a function of environmental factors. Under the assumption of validity, the present model has predictive capabilities which could be used in support of opinions regarding impact levels.

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APPENDIX

This appendix contains computer-generated maps of the Sagavanirktok River Delta depicting results of fish model simulations. Listed in chronological order for the period 9 July-28 July, the maps denote the simulated daily distributional patterns of 200 Arctic cisco. Figure A-1 shows the fishs' random distribution at the start of the 20-day simulation period. Numbered circles on the maps indicate the location of LGL's directional fyke net stations.

