Sea Surface Temperature and the Pre-Season Prediction of Return Timing in Fraser River Sockeye Salmon (*Oncorhynchus nerka*)

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Abstract

BLACKBOURN, D. J. 1987. Sea surface temperature and the pre-season prediction of return timing in Fraser River sockeye salmon (*Oncorhynchus nerka*). p. 296–306. *In* H.D. Smith, L. Margolis, and C. C. Wood [ed.] Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

A simple temperature-displacement model is proposed to account for the annual variation in run timing in Fraser River sockeye salmon (*Oncorhynchus nerka*) stocks. Results of the application of the model show that sea surface temperature (SST) in the central Gulf of Alaska is positively related to annual return timing for seven stocks of Fraser River sockeye and alone accounts for between 30 and 94% of the variation in timing from 8 to 31 years of data. That part of the Gulf and time of year showing the strongest statistical relationship vary in an apparently logical manner from stock to stock. Predictions of the general utility of the model are supported by timing data from four stocks of sockeye returning to the northern Gulf of Alaska. The consequences of using specific areas of the Gulf in this method are discussed, with the 1985 Fraser sockeye run as an example.

Résumé

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Un modèle simple température-déplacement est présenté pour expliquer la variation annuelle du moment de la remontée des stocks de saumon nerka (*Oncorhynchus nerka*) du fleuve Fraser. L'application du modèle a permis de noter que la température de la surface de la mer dans la partie centrale du golfe de l'Alaska présentait une corrélation positive avec le moment de la remontée annuelle de sept stocks de saumon nerka du fleuve Fraser et permettait à elle seule d'expliquer de 30 à 94 % de la variabilité du moment de la remontée ceci pour de 8 à 31 années de données. La partie du golfe et le moment de l'année présentant la plus importante relation statistique semblent varier de façon logique entre les stocks. Les prévisions relatives à l'utilité générale du modèle sont appuyées par les données sur le moment de remontée de quatre stocks de saumon nerka revenant dans la partie nord du golfe de l'Alaska. On traite des effets de l'utilisation de zones précises du golfe en prenant comme exemple la remontée du saumon nerka de 1985 dans le fleuve Fraser.

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Introduction

Knowledge of the long-term mean date of return timing for each Fraser sockeye stock has been an integral part of sockeye management by the International Pacific Salmon Fisheries Commission for many years (Henry 1961; Killick 1955; Verhoeven and Davidoff 1962). Interannual variation in run timing of major stocks can be an important element in the success of the annual fishery management plan. Study of the effects of environmental factors on return timing has included analyses of correlations between these variables. Preseason prediction of the peak timing of the major Fraser sockeye stocks has been a feature of Commission management since 1977 (IPSFC Annual Reports, 1978 through 1984).

A simple model was proposed early in my investigations and formed the basis of further analyses. In this paper I report on the results of comparisons between sea surface temperatures and return timing of several Fraser River sockeye stocks. Results will also be given of the extension of the model to other sockeye stocks in the Gulf of Alaska. Some implications to fisheries management of the use of the method will be discussed.

A Temperature-Displacement Model of Annual Variation in Run Timing of Sockeye Salmon

Development of the Model

Gilhousen (1960) and Killick and Clemens (1963) postulated that variation in the run timing of Fraser River sockeye could be affected by sea surface temperature during their last year. Gilhousen (1960) postulated that the effect of temperature on the fish was physiological, and either (a) direct, presumably on the speed of migration, or (b) indirect, by causing annual variation in the latitudinal distribution of the sockeye. The latter would in turn cause variation in their maturation rate due to exposure to latitudinally varying photoperiod. Killick and Clemens (1963) also implied a physiological effect of latitudinal displacement on run timing due to temperature variation. However, the latter authors thought that cold temperatures in the centre of the Gulf of Alaska might lead to the southward movement of Fraser sockeye into an area of invariably greater food supply which, in turn, might lead to the early onset of migration via increased growth and subsequent early maturation. The opposite tendencies were thought likely to be the result of warm temperatures in the central Gulf.

I considered that both of the foregoing physiological theories had the weakness that they were too specific to Fraser sockeye. Such theories implied that the effect of temperature on the travel speed or maturation of returning sockeye would be likely to have the opposite effect on sockeye returning to the southeastern edge of the Gulf compared to those returning to the northern edge of the Gulf. Of course, this difference is only a theoretical weakness when both sets of stocks are considered together. A simpler, more general, temperature theory was produced based upon the effects of displacement itself, rather than on its possible physiological effect on the onset of migration or on swimming speed. The theory was based on considerations of variation in ocean temperature alone. Some of the general theories of salmon migration have been concerned with the effect of such environmental factors as ocean currents (Royce et al. 1968) or magnetic fields (Quinn 1982). However, at present, predictive models of the interannual variation in salmon run timing cannot be based on ocean currents or magnetic fields due to the scarcity of annual data for these and most other environmental factors in the open ocean.

It is arbitrarily assumed in this model that the horizontal movements of sockeye prior to the last marine winter have negligible interannual variation. This simplifying assumption was borne out by the results of some preliminary analyses. Perhaps the temperature-sensitive displacement is time-dependent or begins only at a certain state of maturity. It is further assumed that the movements of the sockeye during and after the last marine winter fall into two types: (a) relatively slow "non-directed" migration occupying the first several months in response to seasonal changes in surface temperature or in the boundaries of ocean " domains", such as those discussed by Favorite et. al. (1976) and (b) later, relatively rapid, "directed" migration toward the home stream, largely independent of the boundaries of ocean parameters, and lasting no more than about 2 months. The latter independence is supported by a study of Bristol Bay sockeye migration (French and Bakkala 1974). The model assumes that interannual variation in salmon return timing is determined sometime between November and July for various stocks during period (a) above.

The various species of salmon have different centres of distribution in the North Pacific (French et. al. 1976; Takagi et. al. 1981). There are also differences between the centres of distribution of various stocks of one species of salmon from different broad geographical areas, e.g., Western Alaskan sockeye and British Columbia sockeye (French et. al. 1976). These large-scale distributional differences may be, in part, due to optimum ranges of temperature. With no direct supporting evidence, I have assumed that each *stock* of sockeye will have an optimal though not exclusive area of distribution and that it will attempt to stay within some fairly narrow, stock-specific optimum range of sea surface temperature within that area. The location of this optimum temperature range within the optimum areas will change with the seasons: northward (or northwestward in the eastern Gulf of Alaska) in spring and summer; and in the reverse direction in fall and winter. The centres of sockeye abundance will change in concert with temperature changes. The position of the optimum temperatures within the optimum areas in any one season will also vary from year to year. Therefore the seasonal position of the salmon will also show interannual variation.

This simple theory assumes that each year within a general area of stock-specific distribution, the position of the maturing salmon prior to stage (b) — the directed homeward migration — will be determined by the position of the optimum temperatures at that time. For most stocks of sockeye, stage (b) will begin in the spring when ocean temperatures are largely determined by conditions during the prior winter. After an unusually warm winter, the optimum temperatures for a particular stock will be further north than usual. As a result, the salmon of that stock may also be further north than usual in the spring (see Fig. 1).

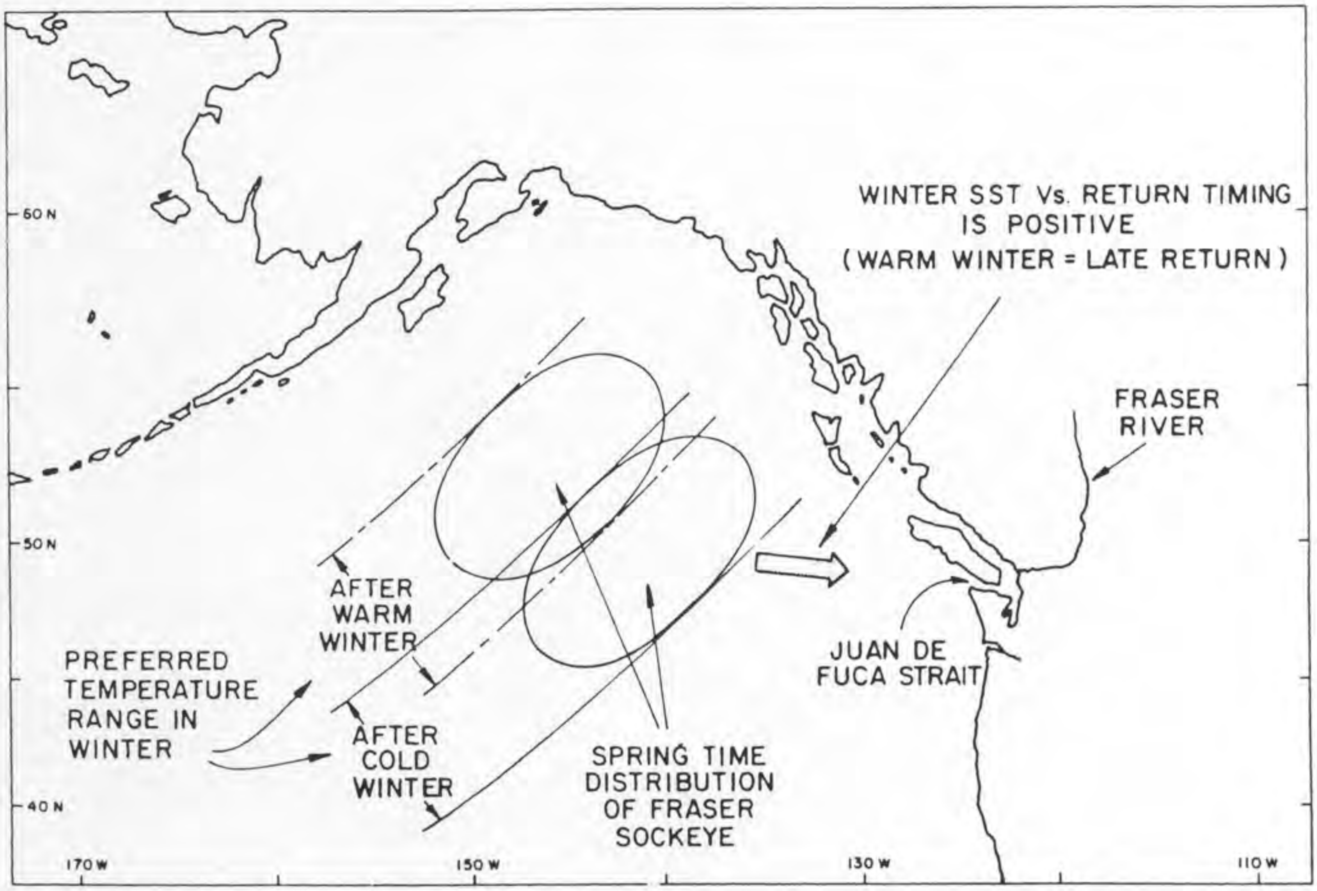

FIG. 1. A simple temperature-displacement model of the return timing of Fraser River sockeye salmon.

Fraser River sockeye stocks return to the homestream in an eastward or southeastward direction (French et. al. 1976). According to the model, very warm winter and spring sea surface temperatures should result in the maturing adults being appreciably further from the Fraser than usual, before they begin their directed homeward migration. It is also assumed that the onset of phase (b) and their speed of migration in either phase (a) or (b) is little affected by temperature, and so the warm temperatures during phase (a) should result in late return timing for Fraser sockeye. Conversely, unusually cold temperatures during phase (a) should result in the displacement of Fraser sockeye to the south and their subsequent early return to the river.

This "displacement" model predicts that salmon returning northward to their home stream will show the opposite relationship between the date of peak return timing and sea surface temperature during the non-directed phase of migration in the last year. Warm temperatures experienced by salmon stocks returning to the north of their winter distribution should cause them to show early return timing.

The model was tested by comparing sea surface temperatures in the Gulf of Alaska with the return timing of various stocks of Fraser sockeye with from 8 to 31 years of data. Testing of the general model was broadened by examination of timing in four sockeye stocks with origins in the northern boundary of the Gulf of Alaska and one originating south of the Fraser. Although the model was developed for sockeye it has also been applied to other species of Pacific salmon (Blackbourn 1984).

Application of the Model

METHODS

Sockeye Timing Data

Return timing is here defined as the peak day of numerical abundance of a stock of Fraser sockeye in outer Juan de Fuca Strait. Gaps in the data (Table 1) result when some sockeye stocks are not numerous enough every year for their timing to be clearly distinguished from that of other concurrent stocks (Henry 1961). Also, in some recent years it has not been possible to specify a peak timing date in Juan de Fuca Strait for several stocks because major portions of the runs returned to the Fraser via another route (Johnstone Strait).

The peak dates (Julian day) (Table 1) were calculated by a variety of methods. These methods changed over the years from simple estimates based on frequent, terminal commercial fisheries in the Fraser River in the 1950's and 1960's to those made by comparisons of graphs of catches by time period from a mixture of test and commercial fishing in Juan de Fuca and Georgia Strait in the 1970's; and by complex run reconstruction methods in the most recent years. Dates of peak timing in the Fraser River and southern Georgia Strait have been adjusted to Juan de Fuca Strait timing with a knowledge of the behaviour of individual stocks by the subtraction of 4 or 5 days from the river dates and 3 days from Georgia Strait dates. For the few years when multiple peaks were apparent, a calculated day of passage of 50% of the

TABLE 1. Adjusted date of peak timing (Julian Day) of Fraser sockeye to outer Juan de Fuca Strait.

Return Year	Early Stuart	Pitt River (5/2)	Horsefly River	Chilko River	Stellako River	Adams River	Weaver Creek
1950	—	—	—	—	—	233 D[b]	
1951	—	—	—	209	—	225	
1952	—	205		207	—		
1953	187	205	203	205	204		
1954	184	198		208	220	240 D	
1955	183	204		212	217	229	
1956	—	203		213	209		
1957	188	202	212	216	219		
1958	195	208		223	239	244 D	
1959	187	217		217	—	235	
1960	—	204		217	—		
1961	185	205	207	210	212		
1962	183	206		211	217	241 D	
1963*[a]	182	203		204	215	222	
1964	—	207		214	213		
1965	183	206	207	209	216		
1966	183	212		211	214	234 D	
1967	191	204		211	223	232	
1968	—	203		211	211		
1969	184	202	204	205	213		225
1970	180	207		216	225	236 D	—
1971	185	208		211	225	230	—
1972	—	204		217	211		223
1973	185	210	210	214	214		231[a]
1974	183	209		215	214	234 D	232
1975	182	206		207	211	228	—
1976	—	200		214	216		223
1977	183	206	206	—	—		229
1978	180	199		216		234 D	236
1979*	182	—		216		217	227
1980	186	—		221			
1981	185	—	218	—			
1982	185	—		219		231 D	
1983	—	—		—		—	
1984	—	—		217		—	
1985	—	—	222	—			

[a]* — Data not included in all analyses (see text).
[b]D — Adams "dominant" cycle.

stock was used as the peak date. There is no objective estimate of the error involved in calculating the peak dates.

Environmental Data

Sea surface temperature (SST) data from B.C. Lighthouse stations were obtained from the Institute of Ocean Sciences, Sidney, B.C. in published and unpublished form (e.g. Giovando 1983). Open ocean sea surface temperature data from ships were obtained from Dr. D. McLain, N.M.F.S., Monterey (unpublished) and from ships, buoys, and satellites from the publication *Oceanographic Monthly Summary* (U.S. National Weather Service, N.O.A.A., Washington, D.C.). The latter SST data were averaged by month over 5° squares of latitude and longitude ('Marsden' squares in Fig. 2).

It was assumed from the results of I.N.P.F.C. tagging during the 1960's that the position of Fraser sockeye in their last marine spring before return would be slightly west of the centre of the Gulf of Alaska at about 53°N and 150°W with perhaps the earlier returning stocks distributed farther to the south (French et. al. 1976).

Analysis

SST data from the above area of the Gulf and from the B.C. coast were compared to the annual peak return timing of Fraser sockeye stocks to Juan de Fuca Strait by simple and multiple least squares regression analysis.

From my (unpublished) analysis of the relatively few I.N.P.F.C. tagged Fraser sockeye which are identified as to stock of origin, certain 5° squares of SST data were initially chosen for comparison with timing data for particular stocks of sockeye. First, mean monthly temperatures by Marsden square were correlated to timing. Then temperature data for adjacent months and areas were pooled and their averages compared with run timing. The largest of the resulting correlation coefficients served to identify the time-area combination yielding maximum explained variability in run timing.

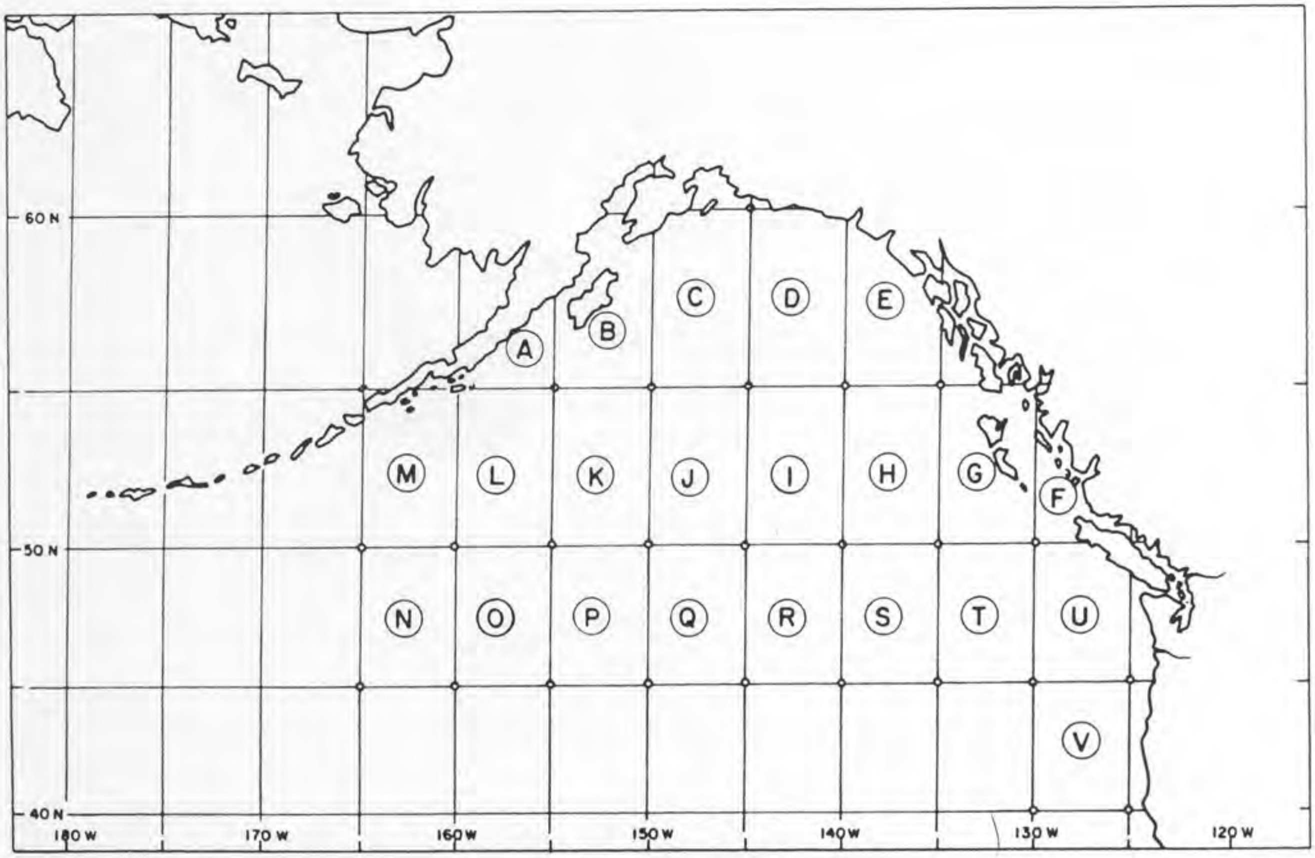

FIG. 2. Author's designation of 5° (Marsden) squares of latitu.le and longitude.

Results and Discussion

A. Sea Surface Temperature (SST) and Fraser Sockeye Timing

The hypothesis was based on very general distributional data, but insufficient tagging data exist on Fraser sockeye salmon in general, or in any particular year, to be sure of their position in the Gulf of Alaska. We know least of all about their distribution during fall and winter (French et. al. 1976). In addition, most of the I.N.P.F.C. tagging occurred during the 1960's, a period of moderate surface temperatures when compared to the cool 1970's and warm early 1980's (Table 3). For these reasons, when it was found that much higher coefficients between SST and timing occurred at a time and place different from that originally chosen in the initial tests, it was felt to be justified on practical grounds that the time and area of highest coefficient was subsequently used in analysis and prediction.

Time and area(s) of highest correlation coefficient between sea surface temperature in the last marine year and the peak return timing to outer Juan de Fuca Strait differed for the adults of seven stocks of Fraser River sockeye (Tables 2 to 4).

The results shown in Tables 2 to 4 and Fig. 3 are consistent with the predictions of the model in that:

a) The sign of the relationship between SST and return timing is positive and statistically significant for these stocks which return to the southeast. From 30 to 94% of the variation in timing is accounted for by SST.
b) For each stock the SST period most highly correlated with run timing occurred well before it returned to the coast.
c) The SST area of highest correlation for each stock was fairly restricted to up to two or three adjacent 5° squares. (Detailed results not shown — D. Blackbourn — in progress).

The distribution of the areas of highest correlation coefficients for four of the stocks (Fig. 3) indicates that they form a fairly consistent pattern, which reflects the pattern of return timing for those stocks. For example, the earliest returning stock (the Early Stuart Lake group) has its SST area to the southwest of the late stock from Adams River (dominant cycle only), with the SST areas of the midsummer stocks from Horsefly and Chilko rivers lying more or less in between them. The difference between the SST areas for Horsefly and Chilko sockeye will be further discussed later. Similarly, the SST period for the Early Stuart stock is earlier than those for the midsummer stocks (Tables 2 to 4 and Fig. 3), which in turn are earlier than those for the Adams River sockeye.

In other studies, sea level pressure and its derivatives such as indices of surface transport have been compared to Fraser sockeye run timing. Likewise, several environmental factors from B.C. coastal areas have been compared with run timing in simple and multiple regression analyses (D. Blackbourn, in progress). None of these factors account for a significant amount of variation in run timing (results not shown) and in most cases such factors do not account for much variation in addition to that accounted for by SST alone.

TABLE 2. Time and area of highest correlation coefficient between sea surface temperature (SST) in the last marine year (Fig. 2) and peak Julian Day of return timing of various stocks of adult Fraser sockeye salmon (Table 1) to Juan de Fuca Strait.

Stock	Years of data	Mean peak timing Julian Day	Strongest relationship with SST		
			Time	Area(s)	Correlation Coefficient(r)
Early Stuart	24	185	Dec. (Yr-1)	Q	0.67**[a]
Pitt River ($^5/_2$'s)	27	205	Dec. (Yr-1)	J & K	0.55**
Horsefly River	9	210	Dec. to Jan.	K	0.97**
Chilko River[b]	31	213	Jan. to March	I	0.67**
Stellako River[b]	22	216	Dec. to March	J	0.70**
Adams River 1950 Cycle "Dominant"	9	236	Jan. to July	D	0.94**
Adams River 1951 Cycle "Sub-dominant"[b]	7	227	Jan. to July	E	0.56[c]
Weaver Creek	8	228	April to May	G	0.84**

[a] * — Significant to P 0.05 level;
** — Significant to P 0.01 level.
[b] 1963 data excluded (see text).
[c] 1979 data included — if 1979 data excluded r = 0.85* (see text).

TABLE 3. Average sea surface temperature (degrees celsius) for various periods and areas of the Gulf of Alaska (see Tables 1 and 2 and Fig 2).

Area Period	Q December (Yr-1)	K Dec. to Jan.	I Jan. to March	D Jan. to July
1950	8.62	5.43	5.58	6.27
1951	7.85	4.59	4.86	—
1952	8.10	4.97	4.87	—
1953	7.97	4.73	5.23	—
1954	7.29	4.84	5.24	7.38
1955	7.57	4.99	5.71	7.24
1956	8.03	4.91	4.81	7.51
1957	8.41	5.23	5.51	7.54
1958	9.91	5.83	6.54	8.94
1959	7.72	5.23	5.92	8.30
1960	8.17	4.89	5.61	7.27
1961	7.14	4.95	5.49	8.07
1962	8.72	5.32	5.75	7.46
1963	7.67	5.28	6.00	8.20
1964	7.71	5.30	5.62	7.52
1965	7.70	4.78	5.03	6.07
1966	7.88	5.13	5.25	6.74
1967	8.16	4.81	5.05	5.39
1968	7.30	4.87	5.13	7.39
1969	6.98	4.43	4.19	6.17
1970	7.37	5.25	5.84	6.98
1971	8.04	5.32	5.20	5.85
1972	8.05	4.85	4.73	5.53
1973	8.40	5.07	5.24	6.16
1974	7.46	5.09	5.06	6.36
1975	7.82	4.99	4.97	6.08
1976	7.40	4.61	5.07	6.57
1977	7.51	4.90	5.78	7.46
1978	7.04	4.42	5.70	6.51
1979	8.37	5.46	5.85	6.88
1980	8.23	5.13	5.74	6.75
1981	7.91	5.55	6.30	7.44

TABLE 3. (*Continued.*)

Area Period	Q December (Yr-1)	K Dec. to Jan.	I Jan. to March	D Jan. to July
1982	7.41	5.09	5.69	6.45
1983	7.84	5.26	6.01	7.47
1984	8.04	5.74	6.56	7.73
1985	7.71	5.85	6.13	6.58

TABLE 4. Regression equations for sea surface temperature and return timing for four stocks of Fraser sockeye salmon (see Tables 1 to 3).

				Regression equation		
Stock	Time	Area	*n*	*r*	*a*	*b*
Early Stuart	Dec. (Yr-1)	Q	24	0.67**[a]	157.37	3.47
Horsefly River	Dec. to Jan.	K	9	0.97**	137.70	14.28
Chilko River	Jan. to March	I	31	0.67**	180.91	5.97
Adams River (1950 Cycle)	Jan. to July	E	9	0.94**	202.93	4.77

[a]** Significant to $P<0.01$ level.

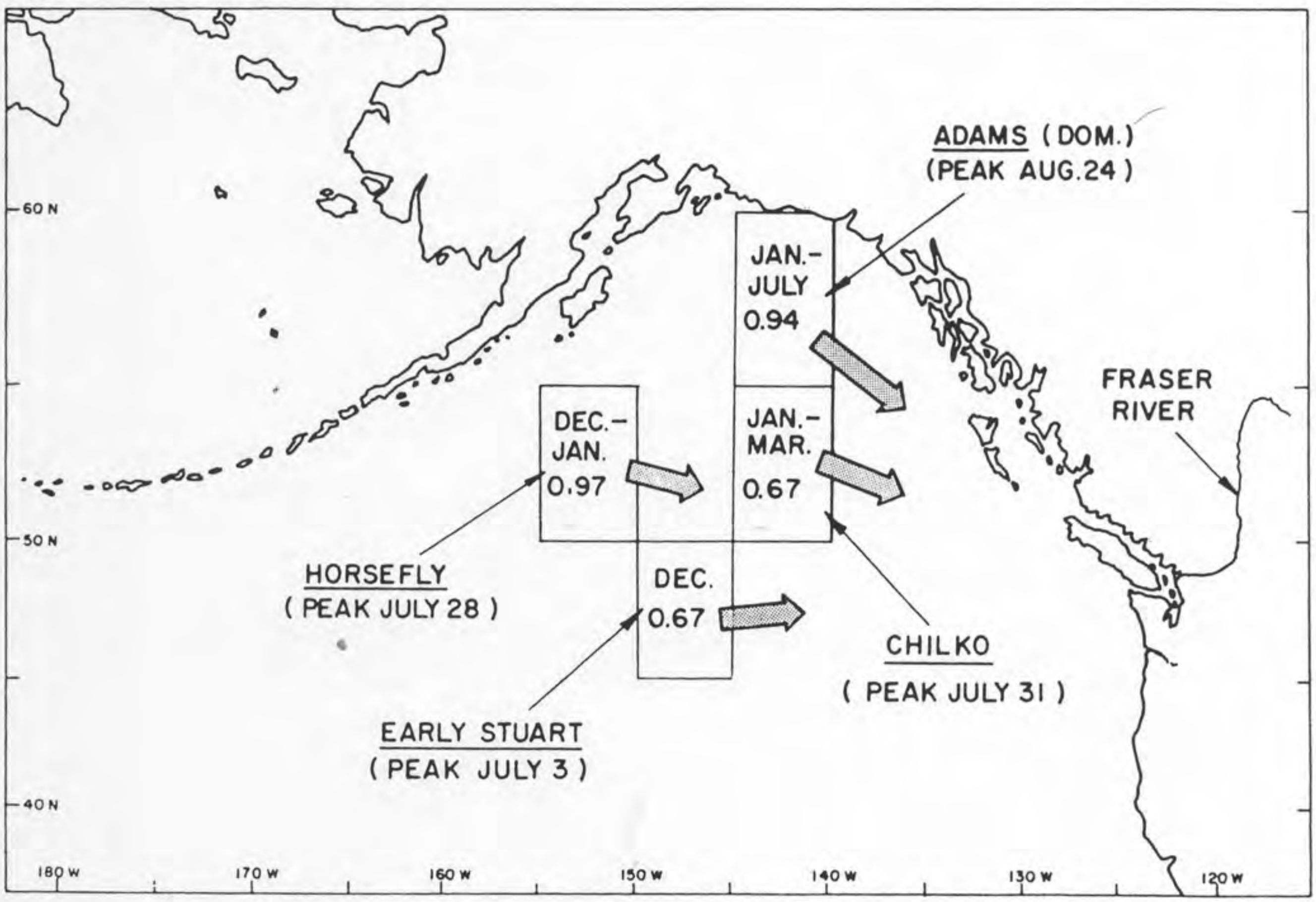

FIG. 3. Areas and times of highest correlation coefficient between sea surface temperature and return timing of various stocks of Fraser River sockeye.

Therefore, it seems likely that useful predictions of run timing in Fraser sockeye will, in future, centre largely on the use of SST from the central Gulf of Alaska, as has been the case over the past several years (IPSFC Annual Reports 1978 through 1984). In some years such as 1963 and 1979 (see Table 1) this method would have given highly anomalous predictions for all (1963) or some (1979) stocks of Fraser sockeye (and see below). These past anomalies are only partly explicable (D. Blackbourn, in progress) and such events can certainly happen again.

Since the prediction of Fraser sockeye run timing began in 1978 the results have been generally good. However, the

TABLE 5. Time and area of highest correlation coefficient between sea surface temperature (SST) in last marine year (Fig 2) and peak return timing of various (non-Fraser) stocks of adult sockeye in the Gulf of Alaska.

Stock	Years of data	Strongest relationship with SST			Source of timing data
		Time	Area(s)	Correlation coefficient (r)	
Chignik River					Conrad (1984)
Black Lake	5	March	L	−0.95**[a]	
Chignik Lake	5	Feb.-March	H & I	−0.99**	
Upper Cook Inlet	18	April	S	−0.48*	A. Kingsbury & C. Meacham (pers. comm.)[b]
		April-June	I	−0.42	
		April—June	J	−0.42	
Copper River	5	April	H	−0.95**	Merritt & Roberson (1983)
		April	I	−0.95**	
Skeena River (Pinkut-Fulton)	13	May	F	−0.78**	R. Kadowaki & P. Starr (pers. comm.)[c]
Quinault River	10	Dec.-Feb.	K	+0.93**	T. Cooney & M. McBride (pers. comm.)[d]

[a] * — Significant to $P < 0.05$ level;
** Significant to $P < 0.01$ level.

[b] Alaska Dep. of Fish & Game, Commercial Fisheries Division, 333 Raspberry Rd., Anchorage, Ak 99502, USA.

[c] Dep. Fisheries and Oceans, Fisheries Research Branch, Pacific Biological Station, Hammond Bay Rd. Nanaimo, BC. V9R 5K6

[d] Quinault Indian Nation, P.O. Box 189, Taholah, WA 98587, USA.

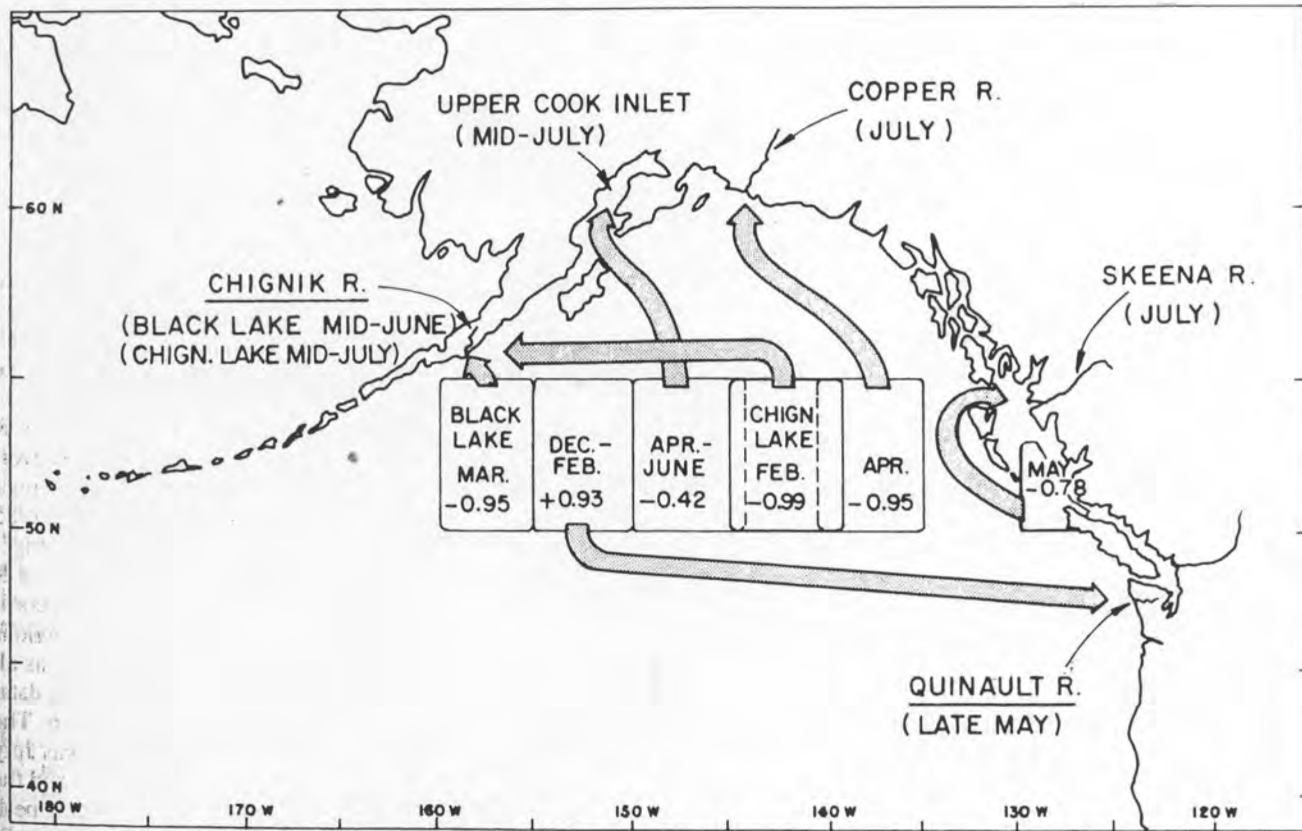

FIG. 4. Areas and times of highest correlation coefficient between sea surface temperature and return timing of various (non-Fraser) sockeye stocks in the Gulf of Alaska.

accuracy of prediction for Early Stuart stockeye timing has been poor for the last few years and more variable than the observed timing data. In other Fraser sockeye stocks the predicted peak date has nearly always been on the same side of the long-term average as the observed peak date, and for most stocks and years within about 2 days of the latter. The largest anomaly of recent years occurred in 1979 when both the Chilko and Adams stocks were predicted to return later than average. Chilko sockeye did return late, but Adams sockeye were extremely early (Table 1). The use of SST data from any part of the northern Gulf of Alaska would not have given a more accurate prediction for Adams sockeye in 1979.

B. Sea Surface Temperature (SST) and Return Timing in Other Sockeye

Table 5 and Fig. 4 show that run timing in sockeye returning to the Quinault River, Washington is similar to early and midsummer Fraser stocks in that it is significantly and positively related to SST in the northwest Gulf of Alaska in winter. However, this stock returns to the coast earlier (late May) than any Fraser sockeye. Two other early stocks which return in June and July, Great Central Lake, and Lake Washington sockeye, also show a positive relationship between run timing and SST in the northwest Gulf although the coefficients are not statistically significant in these latter two cases (results not shown).

Table 5 and Fig. 4 show results consistent with the prediction of the displacement model in that run timing of sockeye returning northward in the Gulf of Alaska to Chignik River, Upper Cook Inlet, Copper River, and the Skeena River is negatively correlated with SST. Several authors have shown negative relationships between SST and run timing in salmon from Western Alaska (Fujii 1975; Nishiyama 1977; Burgner 1980; Mundy 1982). These results also imply that "physiological" models of the effect of temperature on run timing would have to incorporate very different responses for northern sockeye stocks compared to those from the Fraser River.

The SST areas for Chignik sockeye timing data are in general not too far from the areas in which Chignik fish were tagged in the 1960's (tagging data from C. Harris, Fisheries Research Institute, University, Washington, Seattle, Wash. USA 98195, personal communication). The SST areas for Chignik run timing data from the 1960's (Dahlberg 1968) are A, B, J, and R in Fig. 2 (detailed results not given). Figure 4 shows that the SST areas for Black Lake and Chignik Lake sockeye of the Chignik group are fairly widely separated. The latter data are from the years 1978–82 (Conrad 1984). Presumably only the accumulation of more data will enable us to be sure if this spatial separation accurately reflects the apparent influence of SST on run timing in these two substocks. However, the mean peak timing of Black Lake sockeye is about a month earlier than that of Chignik Lake sockeye, so perhaps the separation may bear some relationship to the relative distribution of the two stocks. Some returning Black Lake sockeye are taken in coastal fisheries to the north of the Chignik River (S. Marshall, Alaska Dept. of Fish and Game, Commercial Fisheries Division, 333 Raspberry Rd, Anchorage, Alaska 99502, USA. personal communication). This does not rule out the possibility that these sockeye are distributed to the south and in or near Area L in March (Table 5), since it is known that adult salmon may "overshoot" their natal stream during migration (Blackbourn 1984; French et al. 1976). Owing to the absence of reports on the oceanic distribution of the other two Alaskan sockeye stock groupings (Upper Cook Inlet and to Copper River), SST areas could not be compared to their actual distribution in the Gulf (Table 5 and Fig. 4).

It is certain, however, that the area of highest coefficient for Skeena River sockeye (Pinkut and Fulton stocks) seen in Table 5 and Fig. 4 is more at variance with I.N.P.F.C. tagging data than is the case for most stocks and is different from the known direction of entry of many of these sockeye to the first fisheries, i.e. from the west and northwest. On the other hand there is little data with which to directly confirm or refute the possibility that SST in the Queen Charlotte Sound area to the south of the Skeena River determines the eventual migration behaviour of Skeena sockeye. This result might leave the Fishery Manager who wishes to predict run timing in this stock in a dilemma, for SST data from an area in the central Gulf (say area I in Fig. 2) would have accounted for only about half of the variation in Skeena sockeye run timing from 1970 to the present compared to predictions from SST data from the coastal area or from coastal stations. Of more importance to the manager is the fact that the latter difference would have been even greater in years of extreme run timing in Skeena sockeye. The Skeena sockeye timing data were taken from the test fishery and from run reconstruction. The latter is partly calculated from the former, and gives similar results (Table 5).

C. The Prediction of Run Timing from General and Specific SST Areas

Table 1 shows that since 1953 and prior to 1985 there were 8 years of peak run timing data for Horsefly river (Fraser) sockeye. This contrasts with 31 years of data over a similar period from another midsummer Fraser stock, that from Chilko River. The SST area for Horsefly sockeye is area K in December and January, and that for Chilko sockeye is area I, from January to March (Fig. 2). It was known in advance that the dominant Fraser sockeye stock in 1985 would return to the Horsefly River whereas Chilko sockeye would be relatively few in number.

In many years, predictions of timing made from area K or I would have been very similar (Tables 1 and 3). However, area K contained a very warm SST anomaly in December 1984 and January 1985, whereas by March and April 1985 the SST in area I was only slightly warmer than average. Since a prediction of Horsefly timing in 1985 from area K would have been for a run much later than any on record, a compromise was made prior to the season. The predictions from three SST areas, (K, I, and S), were combined, as all had a strong statistical relationship with Horsefly timing data. The results of these predictions can be seen in Table 6. The previous long-term average Horsefly peak timing was July 26. The final combined prediction was for August 1 and the prediction from the "Horsefly" area (K) alone was for a peak on August 7. The actual 1985 peak occurred on August 9, more than a week later than the official prediction and was the latest timing on record. The 1985 Horsefly sockeye run was also the largest since 1913 and larger than predicted. Although the difference between correlation coefficients of

TABLE 6. Predictions of 1985 Horsefly River sockeye timing made from sea surface temperature (SST) in two areas of the Gulf of Alaska.

Areas of Gulf of Alaska (see Fig. 2)	Corr. coeff. (r) vs. Chilko Timing (N = 31)	vs. Horsefly Timing (N = 8)	Horsefly Peak timing to Juan de Fuca St. 1985 Prelim. Prediction	1985 Final Prediction	1985 Observed Timing	Average Timing
SST in Area K (Western)	0.53**[a]	0.94**	Aug. 7	Aug. 1	Aug. 9	July 26
SST in Area I (Central)	0.65**	0.87**	July 29			

[a]** Significant to $P<0.01$ level.

0.87 and 0.94 is small, the practical outcome of using one or the other was very large in 1985 (Table 6). The need for accurate prediction of run timing is particularly great when there is considerable doubt about stock abundance. From this example it seems not unreasonable to use relatively restricted areas for each stock when predicting the apparent influence of SST on run timing.

Conclusions

1) Sea surface temperature in the Gulf of Alaska is significantly statistically related to adult run timing in seven Fraser and six non-Fraser Gulf of Alaska sockeye stocks or stock-groupings.
2) These relationships are largely consistent with the postulations of a simple temperature-displacement model.
3) Relevant sea surface temperature data are available in time for preseason predictions of approximate adult run timing to be made for many stocks of all species of Pacific salmon.

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