Coastal Circulation and Physical Oceanography of the Scotian Shelf and the Gulf of Maine[1]

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Correlations between annual catch of coastal commercial species of fish and the environmental factors of sea temperatures and St. Lawrence River discharge have led to an investigation of the relationship between the latter. Examining year-to-year variability of monthly means, effects of the St. Lawrence River discharge can be traced by correlation analysis with sea temperatures to propagate from the Gulf of St. Lawrence onto the Scotian Shelf and through the Gulf of Maine at known coastal current drift speeds. Seasonal salinity and transport data support such a flow at least to a section off Halifax on the Scotian Shelf. Within the Gulf of Maine seasonal salinities do not support continuity of flow; however, possible reasons and mechanisms for this are discussed. Other factors such as local river runoff in the Gulf of Maine, Labrador Current, and large-scale weather systems are briefly considered and discussed. It is proposed that the Gulf of St. Lawrence to the Gulf of Maine inclusive be considered as an oceanographic system and events occurring in the southern part on time scales of a month or more are not independent of more northerly events. It is not interpreted that the river discharge is the driving force of such an oceanographic system but rather influences the water properties within the source region of the flow, i.e. the Gulf of St. Lawrence. Some biological implications of the Gulf of St. Lawrence to Gulf of Maine pathway are pointed out.

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Les corrélations entre les prises annuelles d'espèces côtières de poissons de commerce et les facteurs ambiants de température de l'eau et de débit du fleuve Saint-Laurent ont conduit à une investigation de la relation entre ces derniers. Si on examine les variations d'année en année des moyennes mensuelles, on peut retracer les effets du débit du fleuve Saint-Laurent par analyse des corrélations avec les températures de l'eau. Ces effets se propagent depuis le golfe Saint-Laurent, sur le plateau néo-écossais et dans le golfe du Maine à des vitesses de dérive côtière connues. Les données saisonnières de salinité et de transport confirment l'existence d'un tel écoulement, au moins jusqu'à une section du plateau néo-écossais au large d'Halifax. Dans le golfe du Maine, les salinités saisonnières ne confirment pas la continuité de l'écoulement. Nous examinons les raisons et mécanismes possibles de cette condition. Nous discutons brièvement d'autres facteurs tels que le déversement des rivières locales dans le golfe du Maine, le courant du Labrador et les systèmes météorologiques généraux. Nous suggérons que la région qui s'étend du golfe Saint-Laurent au golfe du Maine inclusivement soit considérée comme un tout océanographique et que les événements qui se produisent dans sa partie méridionale, sur échelle temporelle d'un mois ou plus, ne soient pas considérés comme indépendants de ceux qui se produisent plus au nord. Cela ne signifie pas que le débit du fleuve Saint-Laurent est la force motrice d'un tel système océanographique, mais plutôt qu'il influe sur les propriétés de l'eau dans la région d'origine de l'écoulement, i.e. le golfe Saint-Laurent. Nous faisons ressortir certaines implications biologiques du cheminement golfe Saint-Laurent–golfe du Maine.

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FLUCTUATIONS in commercial catches and in the year-class strength of fish and shellfish are well known but their causes are poorly understood. These fluctuations are believed to be due in part to changes in the physical environment of the fish and have been the subject of many investigations (see for example ICNAF Special Publication No. 6: Environmental Symposium, 1965). Although temperature is the factor most often considered (Templeman and Fleming 1953; Taylor et al. 1957; Martin and Kohler 1965; Flowers and Saila 1972), river discharge (Sutcliffe 1972, 1973), winds (Carruthers 1951; Chase 1955), residual drift (Redfield 1939; Colton and Temple 1961), water stability and eddies (Iselin 1939), plus large-scale weather systems (Dickson and Lee 1972; Iles 1973) also have been investigated. These investigations suggest that many environmental factors may be important; consequently, studies of associations between only one environmental factor and fish must be viewed with caution.

Our interest in the relations between commercial catches on the Continental Shelf and environmental factors and among the factors themselves was aroused when, studying Martin and Kohler's (1965) correlations between cod records from George's Bank and temperatures at St. Andrews, N.B., we found similar correlations with discharge records of the St. Lawrence River. Cursory examinations of a few other species were equally interesting. Were the temperatures and discharge somehow related?

Investigating the long-term sea temperature and river discharge records, this paper produces evidence to suggest that the river's effect on temperature is transmitted by the existing coastal circulation southward from the Gulf of St. Lawrence into the Gulf of Maine at certain times of the year. A short discussion of the biological implications of this coastal circulation is to be found near the end of the paper; however, we hope to enlarge upon this and the effects of environmental factors on fish production in a subsequent paper.

Similarities in the year-to-year variations of near-shore sea temperatures of northeastern North America from the Gulf of St. Lawrence southward are well known and have been discussed by several authors (Hachey 1961; Sterns 1965; Lauzier 1965, 1967a, 1972; Colton 1968a, b). These variations paralleled trends in offshore temperatures to 200 m in the Gulf of Maine (Colton 1968a, b), bottom trends on the Scotian Shelf and in the Bay of Fundy, and in the deeper layers of the Laurentian Channel.

The similarity in the year-to-year fluctuations in river discharge from the St. Lawrence River and temperatures at St. Andrews, N.B. was first pointed out by Elizarov (1965). This is not so surprising if one considers the following: the mean annual freshwater discharge of the St. Lawrence system into the Gulf of St. Lawrence is 424 km^3/yr (Trites 1970a), a quantity greater than the sum of the entire freshwater discharge of the eastern United States between Canada and southern Florida, 353 km^3/yr (Meade and Emery 1971). The fresh water from the St. Lawrence moves seaward mixing with sea water to form a low salinity surface layer in the southwestern portion of the Gulf of St. Lawrence, stretching from the St. Lawrence estuary to Cabot Strait.

This layer eventually flows out through Cabot Strait and is the major contributor to the total outflow, approximately 3×10^4 km^3/yr (MacGregor 1956). An outflow of this magnitude, flowing southwest, is enough to replace much of the volume of water on the Continental Shelf between the Laurentian Channel and Cape Cod, 3.6×10^4 km^3 (Barinov and Bryantsev 1972), in 1 yr. Indeed water from the Gulf of St. Lawrence was found by McLellan (1954) to cover the major part of the Scotian Shelf.

It is recognized that temperature and discharge variations must be viewed as part of a larger system of complex interactions and feedback networks. Thus, reasons are not sought for the variability in the sea temperatures beyond those waters directly affecting the Gulf of Maine or the Scotian Shelf, nor in meteorological or hydrological phenomena. The possible role of large-scale weather systems on the hydrometeorological climate of the northwestern Atlantic coast is briefly discussed in a later section.

General Circulation Pattern

In any area, year-to-year changes in the sea temperature or any physical characteristic are determined in part by changes in the character or relative volumes of the constituent water masses. Before examining these details and to emphasize the continuity of the coastal regime, the gross circulation along the northwestern Atlantic coast is presented below and summarized in Fig. 1.

The Labrador Current is a southward-moving continental shelf current containing, relative to its surrounding waters, cold, low salinity water (Iselin 1927). It is comprised of two streams, one inshore on the Continental Shelf and one offshore over the continental slope and the outer edges of the Shelf (Smith et al. 1937). The in-

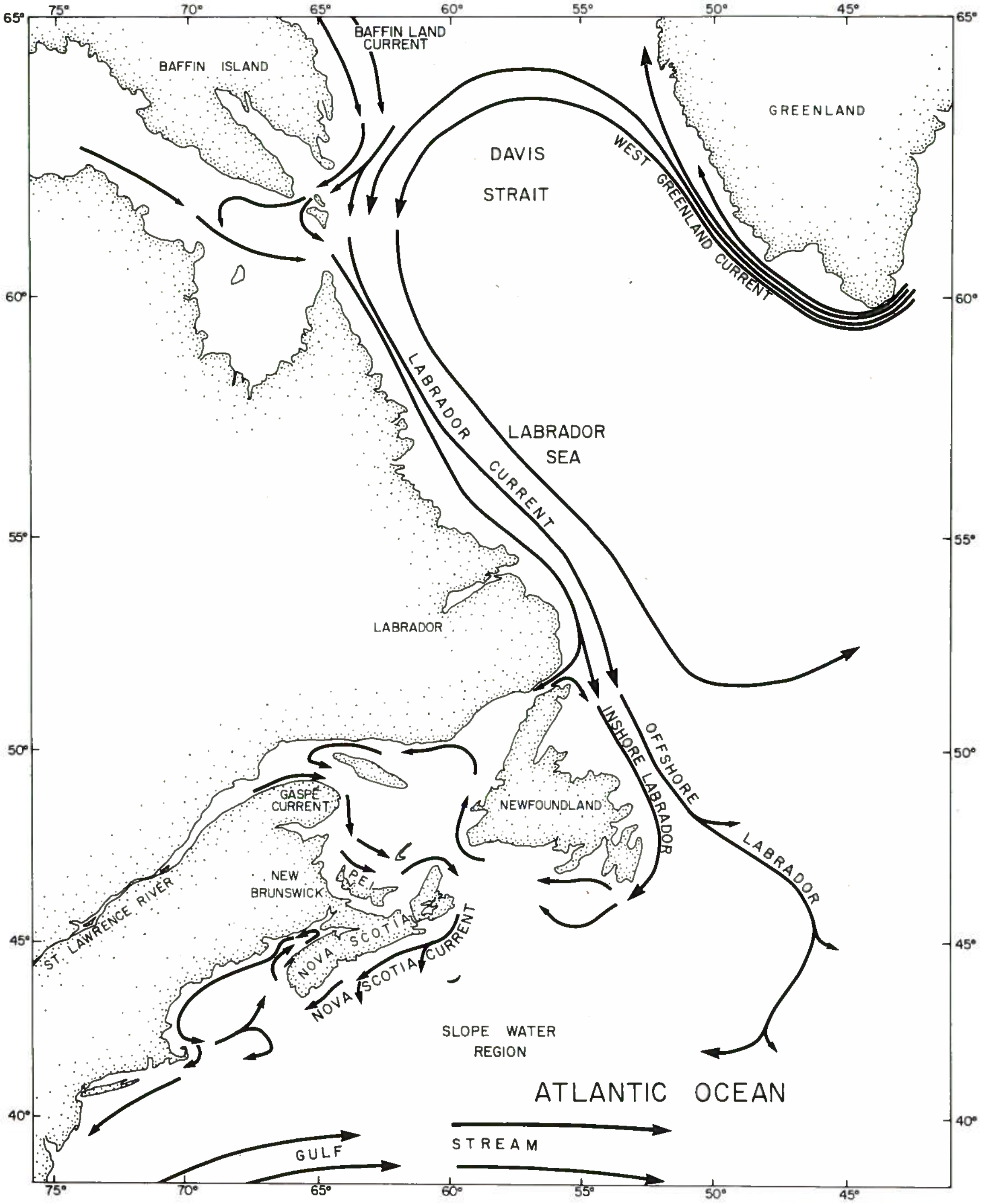

FIG. 1. Northwestern Atlantic coast showing general circulation patterns.

shore stream contains the greater volume of cold water, being a mixture of waters of the Baffin Land Current and water flowing eastward through Hudson Strait (Smith et al. 1937). The offshore stream contains waters characteristic of the warmer West Greenland Current (Smith et al. 1937).

On the journey southward some exchange of Labrador Current and Gulf of St. Lawrence waters occurs at times through Belle Isle Strait (Hachey et al. 1954). As the Labrador Current reaches the latitude of St. John's it splits, the slope branch continuing down the eastern edge of the Grand Banks while the inshore branch follows the Avalon Channel past Cape Race (Smith et al. 1937). The inshore branch loses its arctic characteristics in the vicinity of St. Pierre Bank, and although the current may reach into the Gulf of St. Lawrence (Hachey et al. 1954), the origin of the cold intermediate layer in the Gulf is in situ cooling (Banks 1966). In general, the waters in the Gulf flow northward along the west coast of Newfoundland, are eventually deflected towards the Quebec shore, and flow towards Anticosti (Hachey et al. 1954). Some exchange occurs through Belle Isle Strait as previously mentioned. After the waters pass around the northern end of Anticosti they join with the easterly, fast-flowing Gaspé Current. These waters flow out onto the Magdalen Shallows, slowing down in the process (Hachey et al. 1954). There is an outflow through Cabot Strait named the Cape Breton Current by Dawson (1913). These waters flow southeasterly along Cape Breton and out onto the Scotian Shelf. The waters on the Scotian Shelf are a mixture of Gulf of St. Lawrence water and more saline waters from offshore called Slope Water (McLellan 1954). In general, there is a southwesterly flow parallel to the Atlantic coast of Nova Scotia which was called the Nova Scotian Current by Bigelow (1927). This current rounds the tip of Nova Scotia and at times enters the Gulf of Maine (Bigelow 1927). Here there is an area of relatively intense and constant upwelling (Lauzier 1967b). The circulation in the Gulf of Maine is mainly cyclonic, moving into the Bay of Fundy on the Nova Scotia side and out on the New Brunswick side, then along the coast of the United States as far as Cape Cod (Bieglow 1927). Part of these waters then flow northeasterly to Georges Bank where they again split, part towards the Bay of Fundy and part turning southward to flow back along the United States coast (Bigelow 1927). The amount of flow in each direction depends on the time of year (Bumpus and Lauzier 1965). Tidal mixing is a prominent feature of the Bay of Fundy (Hachey and Bailey 1952). Slope water is a major constituent of Gulf of Maine waters (Hachey et al. 1954). Effects of the Gulf Stream on the Gulf of Maine and Scotian Shelf waters are felt through its effects on the Slope Water characteristics.

Hachey et al. (1954) provide an excellent summary of the general oceanic circulation. Bumpus (1973) provides a more detailed review of the circulation in the Gulf of Maine as well as the circulation southward over the Continental Shelf to Florida.

In summary, then, the oceanic influences that directly affect the waters in the Gulf of Maine or on the Scotian Shelf include the Nova Scotian Current, the Cape Breton Current, and the Slope Water. These in turn are directly affected by the Labrador Current, the Gulf Stream, and the freshwater discharge from the St. Lawrence River. The Gulf of Maine waters are influenced by local freshwater runoff but the small contributions from rivers in Nova Scotia are not felt far beyond their point of discharge. Also affecting the Gulf of Maine and Scotian Shelf waters are on-site meteorological factors, such as solar heating, wind patterns, cloud cover, precipitation, and evaporation.

DATA

All data series in this report are listed in Table 1 with the sources. Some require comment.

SEA TEMPERATURES

Continuous daily sea temperature records of various years' duration have been collected at a number of coastal stations within the area of interest. The stations range from Entry Island, Que. to Boston, Mass. (Fig. 2). All except the lightships contain only surface temperatures. Missing data have been linearly interpolated in time from adjacent points.

Temperature data are also available at Station 27 off St. John's, Nfld., and Prince 5 off St. Andrews, N.B., on a monthly or bimonthly basis for over 20 yr. Temperature data taken at irregular intervals exist at five stations across Cabot Strait (between Cape Ray, Nfld., and Cape North, N.S.) and at eight stations on a line southeast of Halifax to the edge of the Shelf called the Halifax Line.

SALINITY DATA

Continuous long-term records of salinity are scarce. Records of greater than 10 yr duration

TABLE 1. Data series and sources.

Data Series	Source[a]
Sea temperature and salinity	
Boothbay Harbor (temp only)[b]	39
Boston Harbor (temp only)	32–35
Boston Lightship	5–14, 18–21
Cabot Strait	255
Entry Island (temp only)[b]	23
Grand Rivière	23–24
Halifax Line	25
Lurcher Lightship	23
Magdalen Shallows (salinities only)	22
Portland Lightship	5–14, 18–21
Prince 5 (off St. Andrews, N.B.)	25
St. Andrews (temp only)[b]	23
Sambro Lightship	23
Station 27 (off St. John's, Nfld.)	40
River discharge	
Gulf of Maine river (MAINER)	36–38
St. Lawrence, Ottawa, and Saguenay rivers (RIVSUM)	17, 26–30
Air temp	
Eastport	15–16, 31
Fredericton	2
Ottawa	1, 3
Sable Island	4, 15–16

[a] Numbers correspond with those listed in data references.

[b] Recent unpublished data, where needed, were obtained through the kindness of author or agency indicated by reference number.

exist for each of Portland, Boston, and Nantucket lightships. Twenty years' of data are available for Station 27 and Prince 5 on a once or twice a month basis and data on an irregular time basis are also available for Cabot Strait and the Halifax Line stations. Short series of salinity data from the Gulf of St. Lawrence are also used within this report.

ST. LAWRENCE RIVER SYSTEM

The gauged runoffs from the St. Lawrence River (Lake Ontario outflow), the Ottawa River (Grenville Gauge #22B1 to 1962, Carillan Dam Gauge #3118), and the Saguenay River (Centrale d'Ille Maligne) are combined into a river signal called RIVSUM. Within this study the monthly averages from the three gauges are considered to be synoptic.

BAY OF FUNDY AND GULF OF MAINE RIVERS

The gauged runoffs from the Saint John River in New Brunswick, the Penobscot, Kennebec, and Androscoggin rivers in Maine, and the Merrimac River in Massachusetts are considered synoptic for this study (after Meade and Emery 1971) and are combined into a river signal called MAINER. It covers the years 1931–70.

AIR TEMPERATURES

Records of air temperatures from Eastport, Me.; Halifax and Sable Island, N.S.; Fredericton, N.B.; and Ottawa, Ont. are used in this study.

Methods and Statistical Considerations

To investigate the relation between sea temperatures and St. Lawrence River discharge, correlation coefficients were calculated between monthly values of RIVSUM and sea temperatures. The data were separated by month and each of the monthly sets were averaged using 3-yr equally weighted running means. The monthly river signals (RIVSUM) were progressively lagged behind the monthly temperature signals 1 mo at a time (e.g. December RIVSUM vs. January temperature), beginning with no lag and proceeding to a 12-mo lag.

Correlation coefficients were calculated for each lag and each temperature month. This resulted in a 12 × 13 matrix of correlation coefficients where each of the horizontal rows represents correlations at one particular lag time of river for each month of temperature, the vertical columns represent correlations between 1 temperature mo and lags of RIVSUM from 0 to 12 mo, and the left to right diagonals represent correlations between one set of monthly river data and each of the 12 mo of temperature (Table 2).

The temperature stations containing daily records are divided into two groups. Group I contains records of 30 or more years' duration, which necessarily limits the data to surface temperature. The stations include Entry Island, Sambro Lightship, St. Andrews, Boothbay Harbor, and Boston Harbor. Group II has the years 1956–69, in common and contains mostly subsurface temperatures ranging in depth from 20 to 95 m depending on the station. The stations are Halifax Line (Inshore), Lurcher Lightship, Portland Lightship, and Boston Lightship. Entry Island sea surface temperatures are included in the latter group, as subsurface records for these years are not available in the Gulf of St. Lawrence. Correlation coefficients are calculated between these stations and RIVSUM.

Oceanic, hydrological, and meteorological data exhibit marked persistence, a feature that influences the significance levels of correlation coefficients using data of this type. The common procedure of determining significance levels using the total number of pairs of data points and statistical tables of correlation coefficients is based on the assumption that each observation within the individual time series is independent. Statistically this requires the autocorrelation coefficients to be small for lag periods greater than

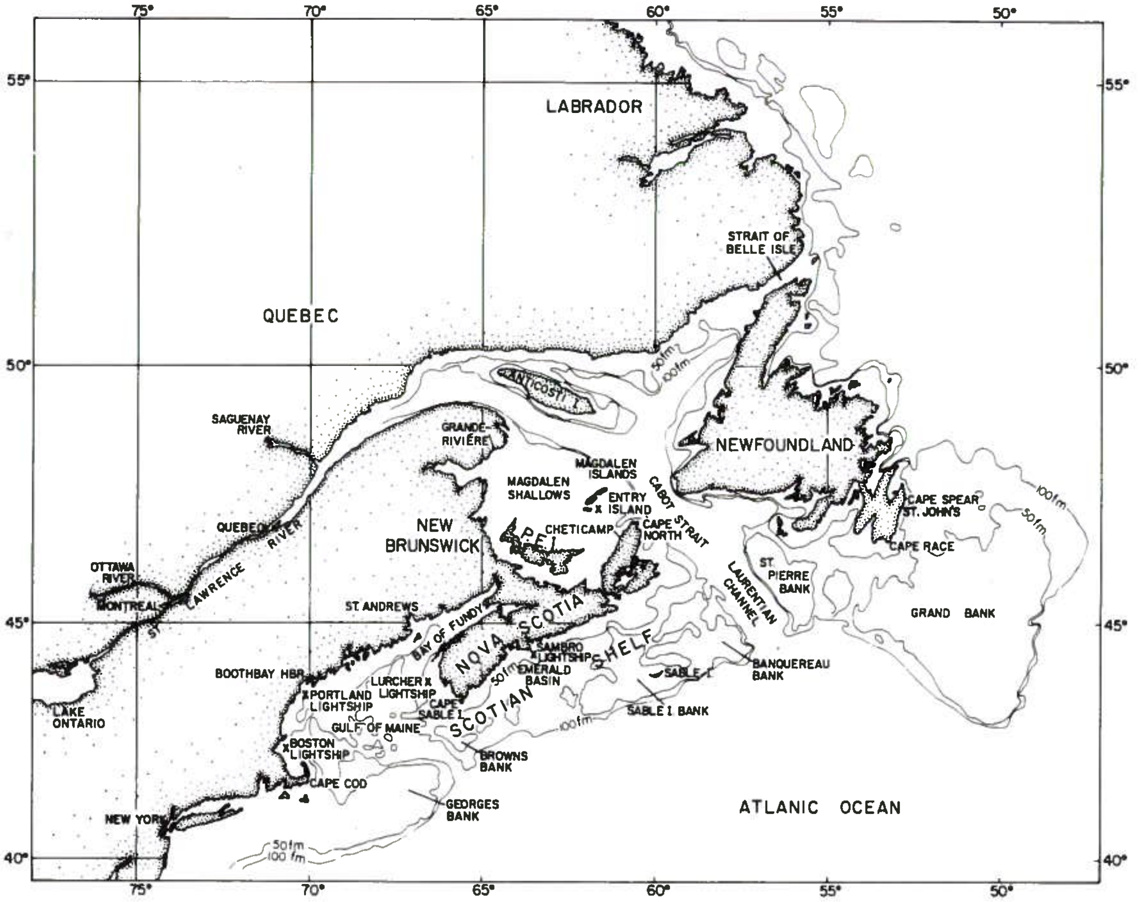

FIG. 2. Location of temperature stations.

zero. The time series being considered have not met such requirements. However, for autocorrelated time series, Bayley and Hammersley (1946) defined "the effective number of independent observations," n^*, by

$$\frac{1}{n^*} = \frac{1}{n} + \frac{2}{n^2} \sum_{j=1}^{n-1} (n - j)[\rho(j\tau)]^2 \qquad (1)$$

where n is the total number of observations and $\rho(j\tau)$ is the autocorrelation coefficient of the j^{th} lag of period τ. As $j \rightarrow n - 1$ the error in $\rho(j\tau)$ can become large due to the decreased number of points included in calculating $\rho(j\tau)$. As a result calculations of n^* within the present study are summed up to and including

$$j = \frac{n}{10} \qquad (2)$$

This value is suggested in Blackman and Tukey (1958) on empirical grounds. For power spectra analysis they require that j should not exceed 10% of the total record in order to hold the rms deviation of each estimate below $\frac{1}{3}$ of its average value. Small changes in n^* were found by increasing j from $n/10$ to $n/2$. On this basis a termination point of $j = n/10$ was considered reasonable. For series being cross-correlated, the effective number of independent pairs was taken to be equal to the lower n^* of the two series being considered. Correlation significance was then determined with $(n^* - 2)$ degrees of freedom. This procedure produced a more representative value of the true statistical significance than estimates solely based on the total number of data points. Hence the significance levels quoted within this paper are based on Bayley and Hammersley's (1946) procedure subject to the conditions in (2).

Results and Discussion

The effects of the discharge from the St. Lawrence River can be traced by correlation analysis to travel at certain times of the year at approxi-

TABLE 2. Correlation matrix between Boothbay Harbor sea temperatures and RIVSUM. The horizontal lines enclose the correlation coefficients for a 3-mo lag of river, the vertical lines enclose coefficients for lags of 0–12 mo of river behind October temperatures and the diagonals follow the progressive lags of May rivers.

No. river months lagged	Month for temp											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	.783	.755	.711	.6	.017	.211	.306	.217	.388	.484	.374	.666
1	.59	.755	.64	.579	.486	.358	.478	.376	.317	.7	.424	.412
2	.409	.577	.653	.345	.345	.414	.507	.46	.343	.599	.655	.418
3	.43	.43	.473	.507	.242	.182	.343	.594	.214	.492	.49	.517
4	.549	.488	.281	.324	.27	.071	.081	.494	.202	.216	.367	.359
5	.447	.607	.37	.149	.107	.128	−.164	.297	.692	.094	.001	.171
6	.295	.447	.475	.291	−.032	.003	−.097	.045	.589	.73	.169	.177
7	−.134	.338	.34	.46	.07	.082	−.198	.062	.463	.843	.644	.265
8	−.234	−.095	.289	.267	.322	.141	−.197	−.03	.474	.786	.809	.633
9	.591	−2.01	−.028	.297	.134	.268	−.14	−.033	.397.	781	.82	.794
10	.773	.665	−.135	.014	.241	.331	.004	−.019	.243	.649	.805	.821
11	.799	.795	.647	−.068	.067	.482	.124	.056	.276	.5	.662	.795
12	.778	.797	.726	.667	.052	.367	.401	.151	.396	.475	.455	.659

mately ocean drift speeds from the Gulf of St. Lawrence, along the Scotian Shelf, and through the Gulf of Maine. Correlation coefficients between river discharge (RIVSUM) and sea temperatures for Group I and II stations showed high values for several river months (the diagonals in Table 2). For Group I the highest correlation coefficients occurred with March RIVSUM but at various months of temperature depending on the particular station. Sambro Lightship was the exception with the highest value occurring with April river but relatively high values were also observed with March river. For comparison purposes the correlation coefficients for March river (the third diagonal in the matrix) are plotted for all Group I stations (Fig. 3a). For Group II the July river signal showed consistently high values and is therefore plotted (Fig. 3b).

The temperature month at which the maximum coefficient occurred varied from station to station but in general increased in time from the river month with distance from the river. The lag times between the river and temperature month at which the peak occurred are listed in Table 3. The peak was chosen as the month of the maximum coefficient unless several months of nearly equally high values occurred. For example, at Boothbay Harbor the peak was chosen at a lag corresponding to the middle of the crest. Peaks occurring at lags of 1 or 0 mo have been disregarded but will be discussed later.

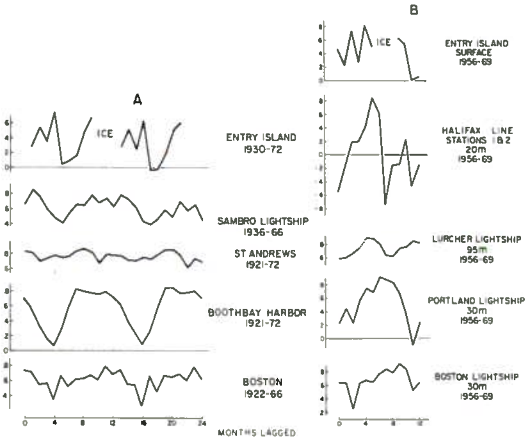

FIG. 3. A, Plots of the correlation coefficients from Group I stations using March RIVSUM, 3-yr running means; B, Plots of the correlation coefficients for Group II stations using July RIVSUM, 3-yr running means. Halifax Line (broken data), June and July RIVSUM, no running means. Dotted lines indicate scanty data, annual ship refit.

If the lag times in Table 3 are assumed to represent the travel time for the effects of a particular month's discharge to be felt at the temperature station in question, then speeds can be calculated if the distance between the river and the temperature station is known. Figure 4 plots distance from the Saguenay River against the lag times for the Group I and II stations as per Table 3. The slopes and intercepts were calculated

TABLE 3. The lag times (from Fig. 4a and b), their statistical significance of the correlation, and the distance from the Saguenay River for temperature stations.

	Station	Years	Distance from RIVSUM (*km*)	Lag time (*mo*)	Statistical significance
Group I	Entry Island	30–72	700	4	.02
	Sambro	36–66	1300	9	.04
	St. Andrews	21–72	1800	8	.001
	Boothbay Harbor	21–72	2100	9	.01
	Boston Harbor	22–66	2325	11	.01
Group II[a]	Entry Island	56–69	700	4	—
	Halifax Line	56–69	1300	5	—
	Lurcher Lightship	56–69	1660	5	—
	Portland Lightship	56–69	2175	6	—
	Boston Lightship	56–69	2325	9	—

[a]Not enough data are available to make meaningful estimates of statistical significance.

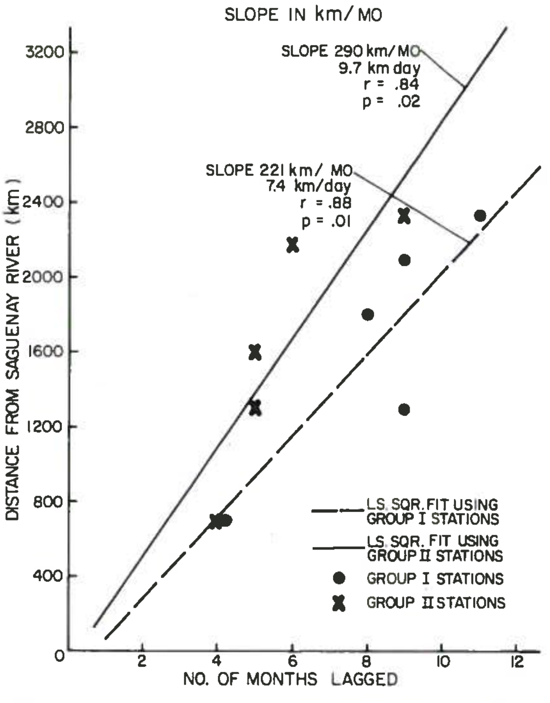

FIG. 4. Plot of distance vs. lag time as determined by correlation analysis.

using a least squares fit. For Group I stations the slope or speed is 7.4 km/day. For Group II stations the speed is approximately 9.7 km/day. Ocean drift speeds calculated by Bumpus and Lauzier (1965) from drift bottle recoveries in the areas under consideration were between 3 and 11 km/day but varied with time of year. Forrester (1971) following oil from a spill originating near Canso, Nova Scotia observed drift speeds of 7 km/day southwestward along the coast of Nova Scotia. Comparison of the average speeds calculated from the correlation analysis with these measured values showed good agreement. The fitted curves do not pass exactly through the origin but are relatively close considering the number of points.

Some questions arise from the correlation analysis. The effect of river discharge on sea temperature is not the same for all months. The highest correlations at all temperature stations occurred with a river month that did not coincide with the maximum discharge month. It is known from drift bottle recoveries (Bumpus and Lauzier 1965; Trites and Banks 1958) that the surface flow on the Scotian Shelf varies seasonally. Seasonal variation in the surface circulation of the Gulf of Maine is also well documented (Bigelow 1927), being closely associated with the wind pattern (Bumpus and Lauzier 1965). These seasonal variations suggest that the effect of river discharge on temperature may be transported only at certain times of the year, thereby offering one explanation for differences in the correlation coefficients between various river months.

Covariances were also calculated between the temperature stations and RIVSUM. Covariances are the unnormalized products of two time series and therefore represent a rough measure of the magnitude of the fluctuations involved. A low covariance means fluctuations of small amplitude. Covariances determined for both Group I and

Group II sea temperature stations showed relatively high values at the peak times listed in Table 3. High covariances were also generally observed with May or April river months. The large river fluctuations during these months, although not correlated with sea temperatures as closely as for other river months, may produce as much effect.

Comparisons in peak lag times made between and within Groups I and II showed reasonable consistency considering the relative crudeness of the technique. The station with the poorest fit in the progressive peak lag times in either group is Sambro Lightship. This may be due to local wind-induced upwelling during the summer (Longard and Banks 1952), which is the season the effects might be expected from a March RIVSUM. Boston Lightship, also located in an area of wind-induced upwelling during summer (Kangas and Hufford 1974), follows the pattern of correlation results. However, the effect of the river does not arrive during the season of expected upwelling.

The correlation peaks at all stations (Fig. 3a, b) recur if the river is either lagged or advanced beyond a time of 12 mo. An example is plotted in Fig. 5. The period of recurrence is 12 mo and is believed to be due to the high autocorrelation or persistence within each particular monthly series. Persistence means 1 yr's discharge is much like the next year's and so with temperature. Three-year averaging contributes to this. Recurrence of the peaks is therefore not unexpected. Persistence can also explain why the correlations are high at small lag times.

To determine the effect of lowest frequency trends in the data, a least squares line was calculated for all data and subtracted out. Correlations run with this trend removed produced similar results to those when correlations were run with the trend included. Slight decreases in both the height of the peaks and the depth of troughs were observed.

The difference in peak lags between stations cannot be accounted for through progression of the seasonal temperature signals. For all stations the minimum temperatures occurred in February or March, while the maxima occurred in August–September for surface values and October–November for subsurface values.

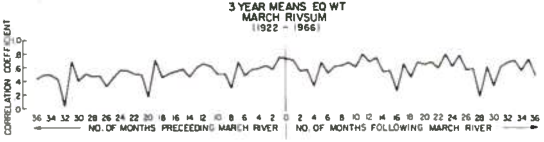

FIG. 5. Plot of Boston Harbour–RIVSUM correlations showing recurring patterns with the sea temperature preceding or lagging the river signal.

Correlation analysis with salinity, similar to that used for temperature, is desirable but long series of continuous data are not available. Seasonal salinities at several locations are available; however, factors important in determining seasonal patterns are not necessarily important in determining the year-to-year variations.

Seasonal salinities are plotted in Fig. 6. The salinity minima progress in time from June–July at Grand Rivière in Quebec to November off Halifax. If these minima are assumed to represent the effects of the peak discharge from the St. Lawrence River (May, see Fig. 7) then it takes 4 mo to travel through the Gulf of St. Lawrence to Cabot Strait (also see Lauzier 1957b) and another 2 mo to reach Halifax. These times agree favorably with the temperature correlation results. Beyond Halifax this simple picture no longer applies. Two reasons might explain this:

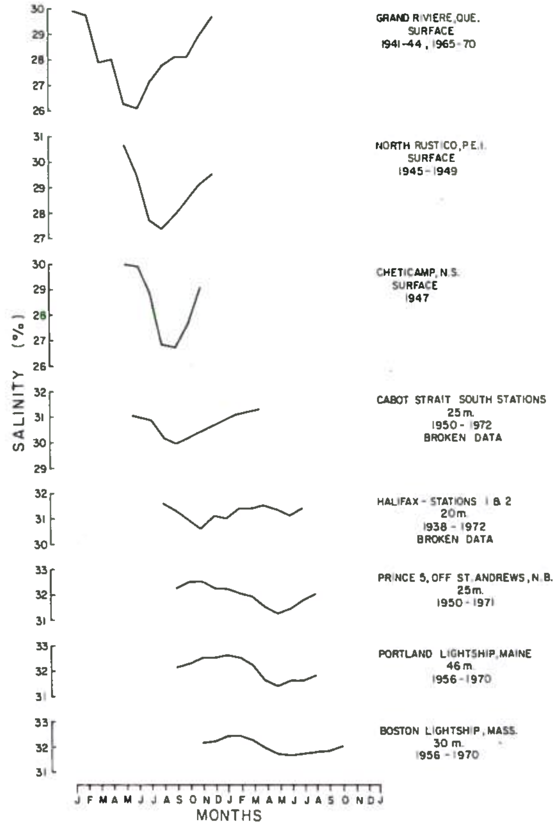

FIG. 6. Seasonal salinity curves at several locations in the Gulf of St. Lawrence, on the Scotian Shelf, and in the Gulf of Maine; Cabot and Halifax Lines 2-mo means (broken data).

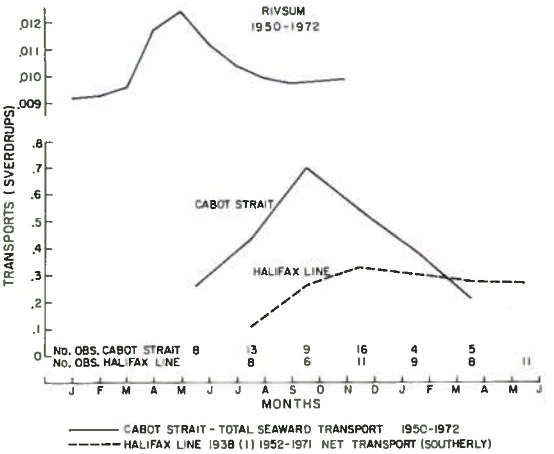

FIG. 7. Seasonal transport curves of RIVSUM, the southerly flow through Cabot Strait, and the net flow through the Halifax Line.

the flow at this time of year may not reach into the Gulf of Maine or it may be masked by local effects. We shall explore this latter possibility in more detail.

Bailey (1957) found a seasonal pattern in the relative amounts of "coastal" to "Slope Water" at two stations in the Bay of Fundy (one station being Prince 5) between 1950 and 1955. He assumed "coastal" water had a salinity of 30.8‰ and "Slope Water" a salinity of 35.2‰ and found the percentage of coastal water to be minimal between October and December and maximal between April and June. If the salinity minimum in November at Halifax progressed into the Gulf of Maine and Bay of Fundy it would be expected sometime between January and March. In fact, a sharp increase in coastal water (thus lower salinity) was observed between December and March by Bailey (1957) preceding the April–June minimum during the 2 yr when data were collected at a central station in the mouth of the Bay of Fundy. At a station closer to the New Brunswick coast (Prince 5) local runoff was more influential and although the amount of coastal water increased at about the same time, the rise was not as steep as at the central station. It was therefore possible that some of the salinity minimum at Halifax does reach Prince 5 but does not appear as a minimum due to masking by local conditions. The departure southward of this former Nova Scotia Current water may explain Bailey's observations that the salinity minimum usually occurred at both stations prior to the peak discharge of the nearby Saint John River, the largest river entering the Gulf of Maine.

The question then arises, if salinity trends are masked, why is the temperature signal observed (Fig. 3a, b)? The answer may lie with Colton (1968b). He observed that during warm years in the Gulf of Maine the boundary between the Slope Water and "coastal" water was nearer the coast than in cold years. Analysis of the Halifax Line data shows that the vertical cross-sectional area of the layer between the warmer upper and lower layers, called the cold intermediate layer by McLellan et al. (1953), is reduced in years of high St. Lawrence discharge, i.e. warm years (Fig. 8). During these warm years the Slope Water is warmer and saltier than normal, being comprised of larger proportions of North Atlantic central water and lesser of "coastal" water (Colton 1968b). At the same time our findings suggest the Nova Scotian Current is delivering warmer and fresher water than normal to the Gulf of Maine. The Gulf of Maine water, being a mixture of "coastal" and Slope Water (Bailey 1957), must therefore be warmer than normal under these conditions. The relative volumes of each type of water would determine whether the salinity would be higher or lower than normal. The mechanisms proposed explain how the temperature signal may be enhanced within the Gulf

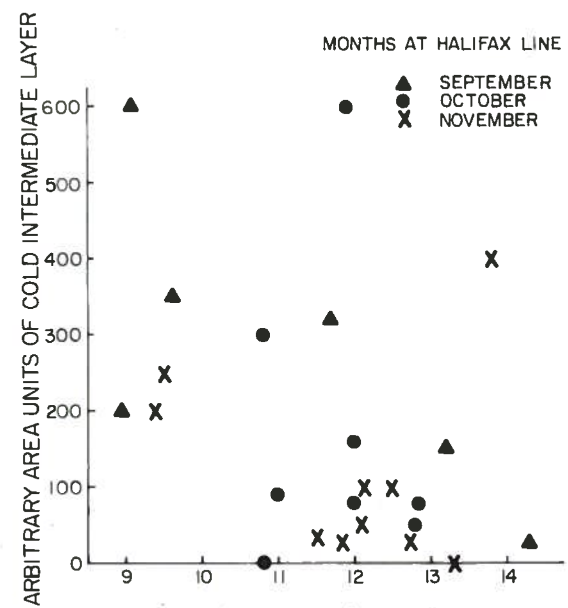

FIG. 8. Plot of the vertical cross-sectional area of the "Cold Intermediate Layer" ($T < 4$ C; $S > 31.5$‰) determined from the temperature–salinity data along the Halifax Line vs. the average discharge from the St. Lawrence River (RIVSUM) for lags of 4, 5, and 6 mo.

of Maine and the salinity signal may be masked. This explanation is, however, speculative.

Some attempts to demonstrate long-term relations between salinity and temperature exist within the literature. Lauzier (1964) has observed that with the deep waters in the Bay of Fundy (175 m) and Emerald Basin (200–240 m), in the long term, increases in temperature are accompanied by increases in salinity and decreases in temperature by decreases in salinity. Colton (1968b) observed similar temperature–salinity relations at 200 m in the Gulf of Maine. Colton also found that these variations occurred due to the composition of the offshore waters as well as the volume of their indraft through the Northeast Channel. It has not yet been shown that such a long-term relation between salinity and temperature exists in the surface layers in the Gulf of Maine or on the Scotian Shelf.

In the Gulf of St. Lawrence evidence suggests that increases in temperature are associated with decreases in salinity and decreases in temperature with increases in salinity. This follows from our correlation that shows high runoff years are associated with high temperature years and Lauzier's (1957a) results that the minimum salinity on the Magdalen Shallows varied inversely with the estimated April to June runoff from the St. Lawrence watershed.

More work is required to establish the long-term temperature–salinity relations in the surface layer in the area under consideration.

Seasonal transport data are even more restricted, especially in spatial coverage, than salinity data. The net transport through the Halifax Line and the southward transport through Cabot Strait are plotted in Fig. 7, along with seasonal pattern of RIVSUM. For Cabot Strait, transports are calculated using the condition of zero net salt flux, as discussed by Forrester and El-Sabh (1972). For Halifax Line, a level of no motion coincident with the seabed is chosen. If the maximum transports are assumed to correspond to peak discharge, the lag time between the river and Cabot Strait is about 4 mo with another 2–3 mo to Halifax. The maximum transports occur at times of minimum salinity (Fig. 6).

Figure 9 shows the seasonal transports for three layers of depths, 0–50 m, 50–175 m, and 175–450 m, as well as the total transport for both the northern and southern halves of Cabot Strait. The amount of data used to calculate these bimonthly transports is not equal for each grouping. Five or more transects are used for each 2-mo period, except January–February. This number is given by El-Sabh (1974) as the minimum required to average out short-term density fluctuations for Cabot Strait. For the period January–February only four transects are available.

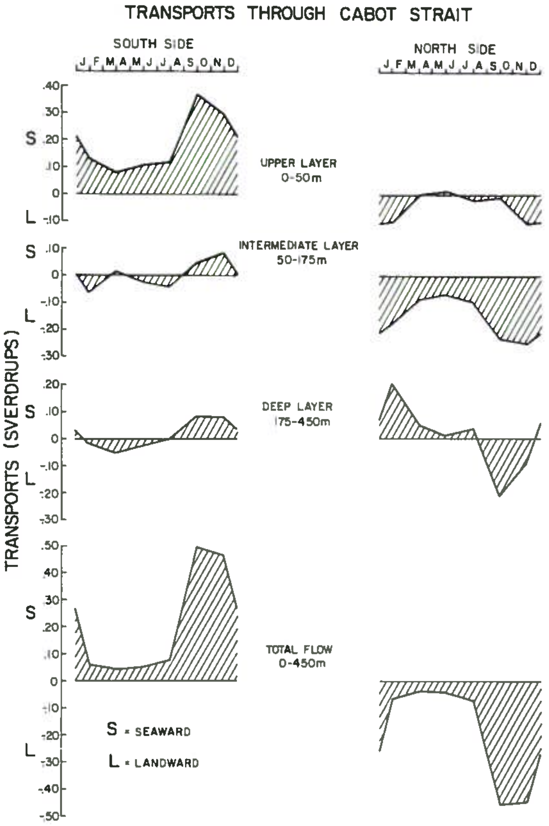

FIG. 9. The seasonal transport through the north and south halves of Cabot Strait with depth.

Seen in Fig 9, the outflow is mainly concentrated in the upper layers of the southern half and is mostly balanced by an inflow on the northern half at intermediate depths. Most of this outflow is derived from the Magdalen Shallows (Hachey et al. 1954; Trites 1970a; El-Sabh 1974). The waters on the Shallows are in turn influenced by the St. Lawrence River discharge (Lauzier 1957a, b). The maximum and minimum transports, both inflow and outflow, for both halves of the Strait occur in September–October and March–April, respectively, agreeing reasonably well with MacGregor (1956) and El-Sabh (1974). The northern inflow through Cabot will be discussed later.

Other Considerations

Gulf of Maine Rivers

Correlation coefficients between temperature stations in the Gulf of Maine and the combined discharge of the five largest rivers entering the Gulf (MAINER) were also calculated. Three Group I temperature stations (St. Andrews, Boothbay Harbor, Boston Harbor), and three Group II stations (Lurcher Lightship, Portland Lightship, and Boston Lightship) were used. For the stations containing the longer temperature records, the correlations are relatively low and produce no apparent patterns. The correlation coefficients seldom reach above 0.7 and only at St. Andrews is a coefficient of 0.8 achieved. This occurs, with April temperatures and February river discharge, that is, at a lag of 2 mo. At subsurface stations for the years 1956–69 high correlation coefficients are observed with the highest occurring with July MAINER. The highest values appear at lags of 4 mo for Portland Lightship and 3–4 mo at Boston Lightship. The statistical significance of these latter values cannot be determined due to the shortness of the record.

These correlation results suggest that year-to-year changes in sea temperature are not determined to a large extent by fluctuations in local discharge. During certain periods of years the discharge may become important but this is not well established. Based only upon correlation analysis, the variations of the St. Lawrence River discharge are more closely associated with the year-to-year changes in the sea temperatures in the upper layers in the Gulf of Maine than are the variations of the local runoff. This is a general result applied to the Gulf as a whole and does not necessarily hold at all locations.

LABRADOR CURRENT

The Labrador Current, as well as wind stress (Murty and Taylor 1970), may be a major influence on the circulation pattern within the Gulf of St. Lawrence, controlling inflowing transport through Cabot Strait. Water entering Cabot Strait, mostly on the north side (Fig. 9), is probably in part of Labrador origin.

Long-term records on the properties of the Labrador Current are scarce. The U.S. Ice Patrol collected oceanographic data between 1935 and 1965 but these observations are primarily limited to the months of June and July. The longest continuous series of data has been collected by the Fisheries and Marine Service Biological Station at St. John's Nfld., which since 1946 has taken measurements at least once per month at Station 27, 4 km off Cape Spear, Nfld.

Correlations between Station 27 temperatures at 30 m depth and Group II stations for the years 1956–69 show coefficients greater than 0.8 at various lags, depending on the temperature station used. However, the peak lags do not show any progressive pattern, being greatest at Entry Island (10 mo) and least at Halifax (7 mo) with the remaining stations exhibiting peak lags between these values.

The trend of the transports of the inshore Labrador Current between 1948 and 1963 calculated from measurements by the U.S. Ice Patrol (Annual Report 1964) shows little resemblance to temperature or salinity variations in the Gulf of St. Lawrence or southward. Indeed the transports change little from year to year, being slightly less than one sverdrup, a value supported by the measurements of Kudlo (1973 and unpublished data). However, the transports measured by the Ice Patrol are based on only one to three cruises each year and usually occur during the late summer. Such limited data make meaningful comparisons difficult.

Within the literature several authors have observed or postulated that the Labrador Current affects the waters of the Scotian Shelf or Gulf of St. Lawrence. Labrador water has been observed on the Scotian Shelf off Banquereau Bank (McLellan and Trites 1951 and unpublished data) but no evidence exists to suggest it reaches farther south (see also Bumpus 1973). The idea that the inshore Labrador Current may reach into the Gulf of St. Lawrence through the north side of Cabot Strait was originally suggested by Bjerkan (1919). This has been supported by observations of cold water moving westward along the northern side of the Laurentian Channel (Lauzier and Trites 1958; Kudlo and Burmakin 1972; Lenz 1973 and unpublished data). The inflow observed through the northern side of Cabot Strait (Fig. 9; Trites 1970a; El-Sabh 1974) is therefore generally considered to be in part of Labrador origin. Whether this inflow is responsive to other driving forces or whether it in itself is a driving force of the water movements in Cabot Strait has yet to be determined.

Lauzier and Trites (1958) observed that long-term changes in the temperature of the deep layer in the Laurentian Channel from its mouth to Cabot Strait were similar to changes in the temperature of the Labrador Current. They also noted that the proportion of Labrador water in the core of the deep water was consistent between years.

The offshore branch of the Labrador Current has not been discussed in detail in this paper as it cannot be traced, as a current, much beyond the Tail of the Grand Bank (Lee 1970). It is shown by Lee (1970) to influence the composition of the Slope Water below 200 m. Any effect of the offshore branch is therefore thought to be indirect through its effect on the Slope Water.

Many questions remain on the role of the Labrador Current in the year-to-year variability on sea temperatures in the Gulf of St. Lawrence and on the Scotian Shelf. The data to date do not allow for detailed analysis of its role.

LARGE-SCALE WEATHER SYSTEMS

What role do the large-scale weather systems play in determining the water properties on the Northwestern Atlantic seaboard? Several authors, notably Bjerknes (1963), Namais (1966), Dickson and Lamb (1972), and Rodewald (1972) have associated changes in the large-scale weather systems with subsequent effects on winds, precipitation, and air and sea temperatures in the North and northwest Atlantic. In particular, shifts in the intensities and in the relative positions of the Icelandic Low and the Bermuda–Azores High (Bjerknes 1963) have been connected with the trends in sea surface temperatures.

Air temperatures within the region being discussed respond to large-scale weather systems. This is suggested on the strength of the similarities between the annual air temperatures of Ottawa, Ont.; Fredericton, N.B.; Eastport, Maine; and Sable Island, N.S., as shown in Fig. 10. The diverse locations and the distances involved between these stations require large-scale phenomena to explain the similarities.

Long-term similarities have been observed between Boothbay Harbor sea temperatures and Eastport, Me., air temperatures by Taylor et al. (1957), and between St. Andrews sea temperatures and Halifax and Sable Island air temperatures by Lauzier (1972). To investigate, correlation coefficients between Group I and II sea temperature stations and Eastport air temperatures were calculated in a manner similar to that described earlier for sea temperatures and river discharge. No large differences were observed between the various sea temperature stations and no trends appeared. Coefficients at small lag times for all stations were generally below .7. These results suggest that air temperatures alone cannot account for sea temperature variability.

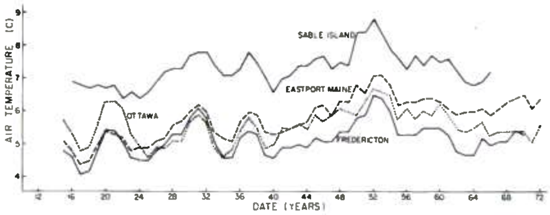

FIG. 10. Plots of the 3-yr equally weighted means of the annual averages of air temperatures at Eastport, Me.; Fredericton, N.B.; Ottawa, Ont.; and Sable Island, N.S.

What then is the role of the large-scale weather systems? As stated previously, these systems will control wind patterns, air temperatures, and precipitation. These several factors act upon the waters within the Gulf of St. Lawrence determining, or at least affecting, the water properties there. These water properties are associated with the levels of the St. Lawrence River discharge, and eventually flow southward over the Scotian Shelf and into the Gulf of Maine. The waters within these geographic areas are therefore affected by this flow as well as by direct hydrological and meteorological factors which in turn are linked back to the large-scale systems. One can view the water properties on the Scotian Shelf and in the Gulf of Maine as being made up of a stationary signal and a moving signal, both signals being determined by the large-scale weather systems. The stationary signal is due to direct effects of hydrological and meteorological factors and the moving signal is due to the oceanic pathway which appears to begin within the Gulf of St. Lawrence and transports water showing effects of more northerly events into the southern sections. The relative importance of the two signals cannot at present be resolved but the existence and the possible importance of the oceanic pathway should be recognized.

BIOLOGICAL IMPLICATIONS

As noted in the introduction, there are a number of correlations between various enivronmental factors and fish production as exemplified by commercial catch statistics on the Continental Shelf. It is difficult to say whether these are direct effects (i.e. optimal temperatures for larvae) or whether the environmental parameters are mere indicators in the local oceanographic climate accompanying other factors, so far scantily measured and poorly documented in terms of long time series. Surely, however, some of the relations must originate in primary production and thus in the availability of nutrients.

From the descriptive oceanography of earlier sections one can point to a number of areas where subsurface water would be mixed with or transferred to the surface. In the Cabot Strait transports, as shown by Trites (1970a) with current meters, El-Sabh (1974), and in Fig. 9, it is seen that most of the flow into the Gulf of St. Lawrence is below 50 m while the outgoing flow is above 50 m. This indicates translation of subsurface water to the surface somewhere in the Gulf, surely accompanied by nutrient enrichment of surface layers to some degree. Specific areas of upwelling in the Gulf of St. Lawrence have been noted: along the north shore (Lauzier et al. 1957) thought to be wind induced (P. Vandall personal communication), the St. Lawrence estuary influenced by the river (Neu 1970 and unpublished data; Steven 1971 and unpublished data), the New Brunswick shore of the western Gulf (Lauzier 1967b), a possibility of upwelling just southwest of the Magdalen Islands (Lauzier 1967b), and anticlockwise gyres both stationary (west of Anticosti Is.) and moving (Blackford 1967; Trites 1968 and unpublished data; El-Sabh 1974). Internal tides in the area of the estuary (Forrester 1970) may contribute to mixing of deeper with upper water there (Forrester 1974). Several of these areas can be identified in appropriate infrared satellite photographs we have examined, and the correspondence with some of the maps of fish stocks in the Gulf of St. Lawrence (Kohler 1968), especially herring, is interesting.

Any or all of these areas could be affected to a greater or lesser degree by river discharge as well as the other factors involved in Gulf circulation and could be enhanced or dampened. No attempt is made here to assign relative biological importance to these areas, although highest productivity and phytoplankton concentrations as presented by El-Sabh (1974) were in the northwest Gulf near the mouth of the estuary.

Continuing from Cabot Strait to the southwest along Nova Scotia, at least three phenomena have been identified which could be affected one way or another by coastal flow of varying quantity and quality. Lauzier (1967b) has noted two upwelling areas as indicated by seabed drifters. One is at the northeast corner of Nova Scotia next to Cabot Strait, the other to the southwest adjacent to the Gulf of Maine. The latter, in particular, is highlighted by biological activity, being the area of greatest lobster catch in all Nova Scotia, and has the largest nonbreeding concentration of surface feeding sea birds in the northwest Atlantic (R. G. Brown personal communication). In between, along the Nova Scotia coast, is apparently a narrow band of intermittent upwelling promoted by favorable winds (Hachey 1937; Longard and Banks 1952). Its influence must be quite nearshore; otherwise, Lauzier's drifters would have been affected — the lack of returns between the two areas mentioned above is striking. A possible cause of the upwelling off southwestern Nova Scotia is discussed in Garrett and Loucks (1976).

It is difficult to see how coastal flow from Cabot Strait exerts influence in the Gulf of Maine except indirectly or through the temperature correlations already discussed. However, mixing from the Bay of Fundy and coastal upwelling (Graham 1970; Kangas and Hufford 1974) are certainly nutrient sources and might respond in some fashion. We hope to enlarge upon at least the effects of some environmental factors on commercial fish catch in a subsequent paper.

Summary

In this paper, attention has been focused on several individual factors, in particular the St. Lawrence River system, which are thought to be related to year-to-year fluctuations in temperature on the Scotian Shelf and in the Gulf of Maine. It is recognized that other factors may also affect and indeed may be as important as those already discussed. The relative importance of the many factors in determining changes in the temperature and salinity in the Gulf of Maine or on the Scotian Shelf is unknown. Therefore, the importance of the role of the St. Lawrence River discharge must be viewed cautiously. It cannot be considered as uniquely determining these fluctuations or indeed of being the major contributor. Correlation analysis does suggest that it is in part influential in determining these sea temperature changes.

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