PROBABILITY FORECASTS OF WATER SURFACE TEMPERATURES OF THE ST. LAWRENCE RIVER BETWEEN KINGSTON, ONTARIO AND SOREL, QUEBEC

by

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INTRODUCTION

The St. Lawrence River, the outlet for the Great Lakes, is ice covered from Lake Ontario to near Montreal for about three months of the year. The ice cover has serious consequences for both navigation, which must cease operations during this period, and power production, which is reduced because of frictional head losses. Recent proposals to lengthen the navigation season have increased interest in the investigation of forecasting temperatures from which the time of ice formation can be inferred. Since major construction of the St. Lawrence Seaway and Power Project changed the thermal regime of the river in 1958, only a relatively short period of experience with freeze-up under these conditions is available.

SYNOPSIS

This paper outlines the methods used in the development of a water surface temperature model and the derivation of a method of forecasting water surface temperatures.

From the results of the study, it appears that useful forecasts of water surface temperatures, from which freeze-up dates on the St. Lawrence River can be inferred, are practicable. The use of currently available monthly forecasts of levels and flows combined with Airborne Radiation Thermometer (ART) data and forecasts of air temperature, provide the necessary data for forecasting water surface temperatures.

PROBLEM AREAS WITH RESPECT TO ICE FORMATION

Situated in the temperate zone, the Great Lakes-St. Lawrence River system is subject to large seasonal changes in temperature which are reflected in the water surface temperatures of Lake Ontario ranging from a high of about 70°F in mid August to a low of about 34°F near the end of February. As the winter season approaches, the water is gradually cooled as it moves from the lake down the river. As cooling takes place, an ice front forms near Montreal and moves upstream toward the lake.

At present, navigation on the St. Lawrence River below Montreal operates at most times throughout the winter with the assistance of ice breakers. However, as the ice front moves upstream from Montreal Harbour, the South Shore Canal, which extends from Lake St. Louis to the harbour and bypasses the Lachine Rapids, becomes ice covered, halting navigation between Montreal and Lake Ontario. Approximately 10 miles upstream, at the head of Lake St. Louis, is located the Beauharnois Power Development and the Beauharnois Locks of the St. Lawrence Seaway System. Water is supplied to the Beauharnois powerhouse via the power and navigation canal which extends about 15 miles to Lake St. Francis. The major portion of flow from Lake St. Francis is diverted down the canal with a minimum of 10,000 cfs being passed through control works at the head of the Coteau Rapids to the Cedars powerhouse.

The maximum flow in the Beauharnois Canal is restricted to 255,000 cfs to maintain acceptable velocities for navigation. As the ice front approaches this area, ice booms are installed in the canal to lessen the danger of ice jams and to promote the formation of a stable ice cover. There are a series of eight booms, five of which extend across the full width of the canal and close off the canal to navigation. Installation of these booms and the removal of navigation aids usually lasts one to two days and must be accomplished in advance of ice formation.

Lake St. Francis, a wide and shallow expanse of the St. Lawrence River, extends westward for about 25 miles to near Cornwall where the Moses-Saunders Power Dam is located. Navigation proceeds past this point via the Eisenhower and Snell Locks near Massena, N.Y. Immediately upstream of the power development is Lake St. Lawrence, created as a result of the raising of water levels by construction of the power dam. Upstream near Morrisburg the channels become constricted to the Prescott-Odgensburg area. As part of the St. Lawrence Power and Navigation Project, dredging was done in this reach of the river to provide navigable depths and velocities suitable for ice formation. Velocities in certain of these areas, however, are in excess of the recognized maximum for ice packing. To lessen the danger of ice jams and to promote the formation of a stable ice cover, the power entities install six ice booms above these critical sections of the river, two of which cross the navigation channel. The most upstream of these ice booms extends across the river between Ogdensburg and Prescott. A stable ice cover forms between this boom and Lake Ontario without serious problem. Figure 1 is a plan of the St. Lawrence River from Kingston to Lake St. Peter indicating the critical locations previously mentioned.

Since economic benefits may be derived from an extended navigation season, the timing of closure and opening of the ice booms is of critical importance. In order to provide some suitable information upon which these decisions might be based, studies were undertaken to develop a method of forecasting water surface temperatures at Montreal, Beauharnois and Cornwall.

METHOD OF COMPUTING WATER SURFACE TEMPERATURES

In a previous study Witherspoon and Poulin(1) developed a model to calculate the heat loss in the St. Lawrence River between Kingston and Cornwall. The purpose of the study was to determine if a satisfactory model could be found for the cooling of lake water as it moved down river, and the prediction of water surface temperatures along the length of the river. The Airborne Radiation Thermometer (ART) as described by Richards(2) provided a useful instrument in determining the water surface temperature profile of the river. The Meteorological Service of Canada was using such an instrument and cooperated with the Inland Waters Branch to fly the main channel of the river between Kingston and Lake St. Peter. Flights made on December 9 and 18, 1968 and November 17 and 25 and December 4, 12 and 30, 1969, provided water surface temperatures at two-mile intervals along the main channel of the river. ART temperature measurement accuracy was verified by surface measurements within 1°Fahrenheit.

The study required the development of a model which would provide an adequate simulation of the temperature of the river surface as verified by the ART flights. Using an empirical relationship for the heat loss from an open water surface, as proposed by the Joint Board of Engineers(3), water surface temperatures were calculated with respect to time and discharge. The model was of the form

$$T_1 = T_0 - CK \qquad (1)$$

where T_1 = water surface temperature at downstream end of section, in °F

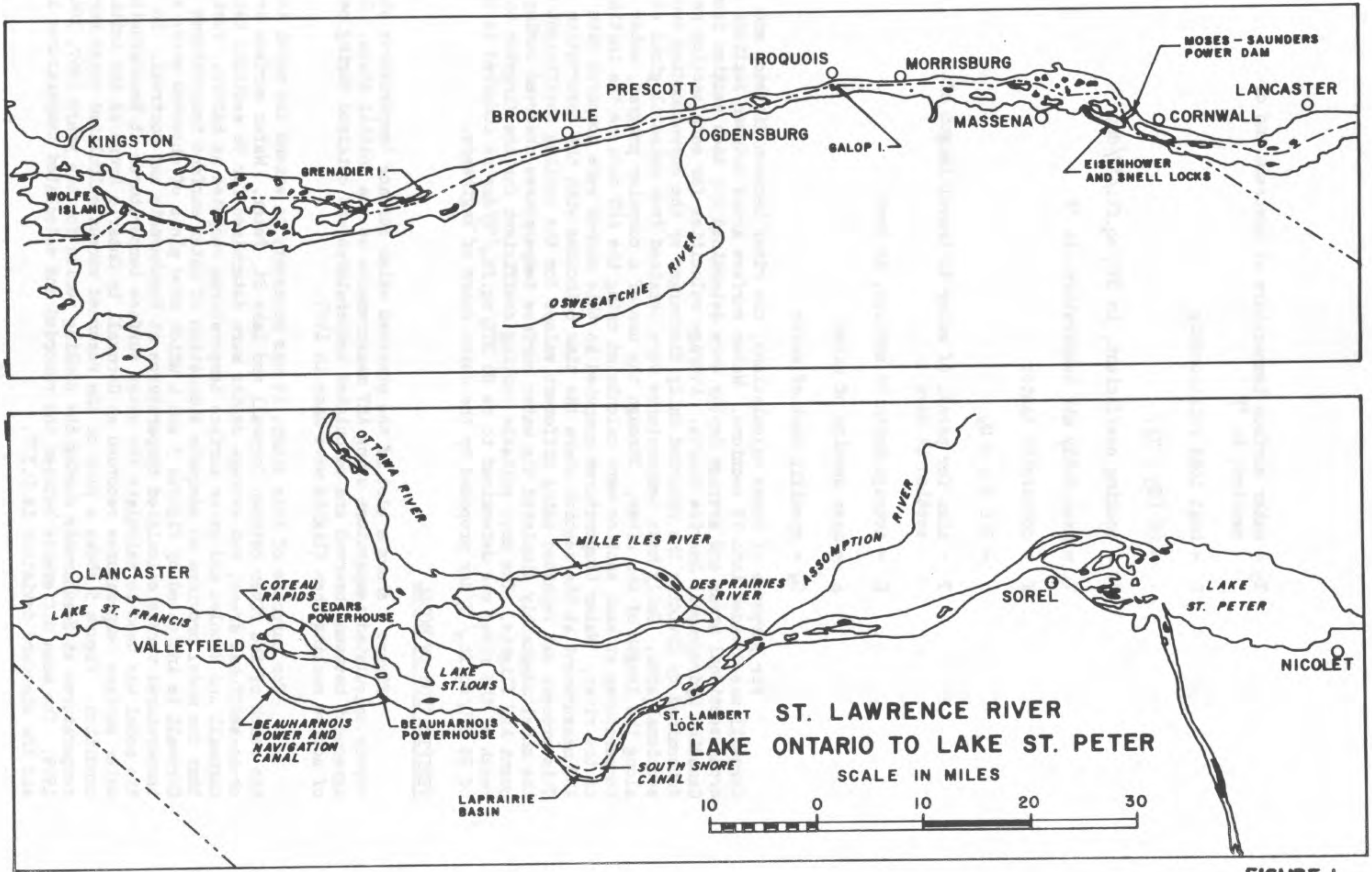

KINGSTON
WOLFE ISLAND
GRENADIER I.
BROCKVILLE
OSWESATCHIE RIVER
PRESCOTT
OGDENSBURG
IROQUOIS
GALOP I.
MORRISBURG
MASSENA
MOSES – SAUNDERS POWER DAM
EISENHOWER AND SNELL LOCKS
CORNWALL
LANCASTER
LANCASTER
LAKE ST. FRANCIS
COTEAU RAPIDS
CEDARS POWERHOUSE
VALLEYFIELD
BEAUHARNOIS POWER AND NAVIGATION CANAL
BEAUHARNOIS POWERHOUSE
OTTAWA RIVER
LAKE ST. LOUIS
LAPRAIRIE BASIN
SOUTH SHORE CANAL
ST. LAMBERT LOCK
MILLE ILES RIVER
DES PRAIRIES RIVER
ASSOMPTION RIVER
SOREL
LAKE ST. PETER
NICOLET
ST. LAWRENCE RIVER
LAKE ONTARIO TO LAKE ST. PETER
SCALE IN MILES
10
0
10
20
30

FIGURE I

T_O = water surface temperature at upstream end of section, in °F

C = heat loss relationship

$= CC\ (T_O - T_A)$

CC = cooling coefficient, in BTU/sq.ft./°F/day

T_A = mean daily air temperature, in °F

K = conversion factor

$= T/D \times \rho \times C_W$

T = time for parcel of water to travel length of section in days

D = average depth of section, in feet

ρ = mass density of water

C_W = specific heat of water

For purposes of these calculations, the river between Kingston and Cornwall was divided into 73 sections. Water surface areas between sections and cross-sectional areas and average depths were determined for each section from Canadian Hydrographic Service charts. Average velocities for each section were determined by dividing the recorded daily discharged by the corresponding cross-sectional area. Daily mean temperatures were obtained from meteorological stations along the length of the river. Through the use of a computer program, water surface temperatures at each section were calculated using the ART data as the initial state of the river. Water temperatures computed in this manner were compared with the next ART measurement at the section where the time coincides with the observation time. This process was repeated using different values for the cooling coefficient until the model adequately simulated the water surface temperatures observed during subsequent ART flights. The most suitable cooling coefficient for the Kingston to Cornwall reach of the river was determined to be 86 BTU/sq.ft./°F/day as compared to the value of 95 BTU/sq.ft./°F/day proposed by the Joint Board of Engineers.

VERIFICATION OF MODEL

Figure 2 shows a plot of the observed water surface temperatures at Cornwall versus calculated temperature using ART measurements as the initial state. Good agreement between observed and calculated temperatures was obtained during periods of active cooling when flights were made in 1969.

For purposes of this study, it was necessary to extend the model to include the reach of the river between Cornwall and Lake St. Peter. Water surface areas, cross-sectional areas, and average depths were determined for 96 sections between Cornwall and Nicolet and water surface temperatures computed as before. Verification that the model provides an adequate simulation of water surface temperatures below Cornwall is indicated by Figures 3 and 4 which show plots of observed water surface temperatures versus calculated temperatures at Beauharnois and Montreal. In addition the model was used to calculate the water surface temperatures at Beauharnois using water surface temperatures recorded at Cornwall by Ontario Hydro as the initial state condition. Figure 5 shows a plot of the recorded versus calculated water surface temperatures at Beauharnois during the cooling period for the years 1967, 1968 and 1969. The mean difference between the recorded and calculated temperatures is 0.0°F and the standard deviation is 0.5°F.

FIGURE 2

PLOT OF CALCULATED TEMPERATURES
USING A.R.T. MEASUREMENTS AS INITIAL STATE
VS
OBSERVED TEMPERATURES AT CORNWALL

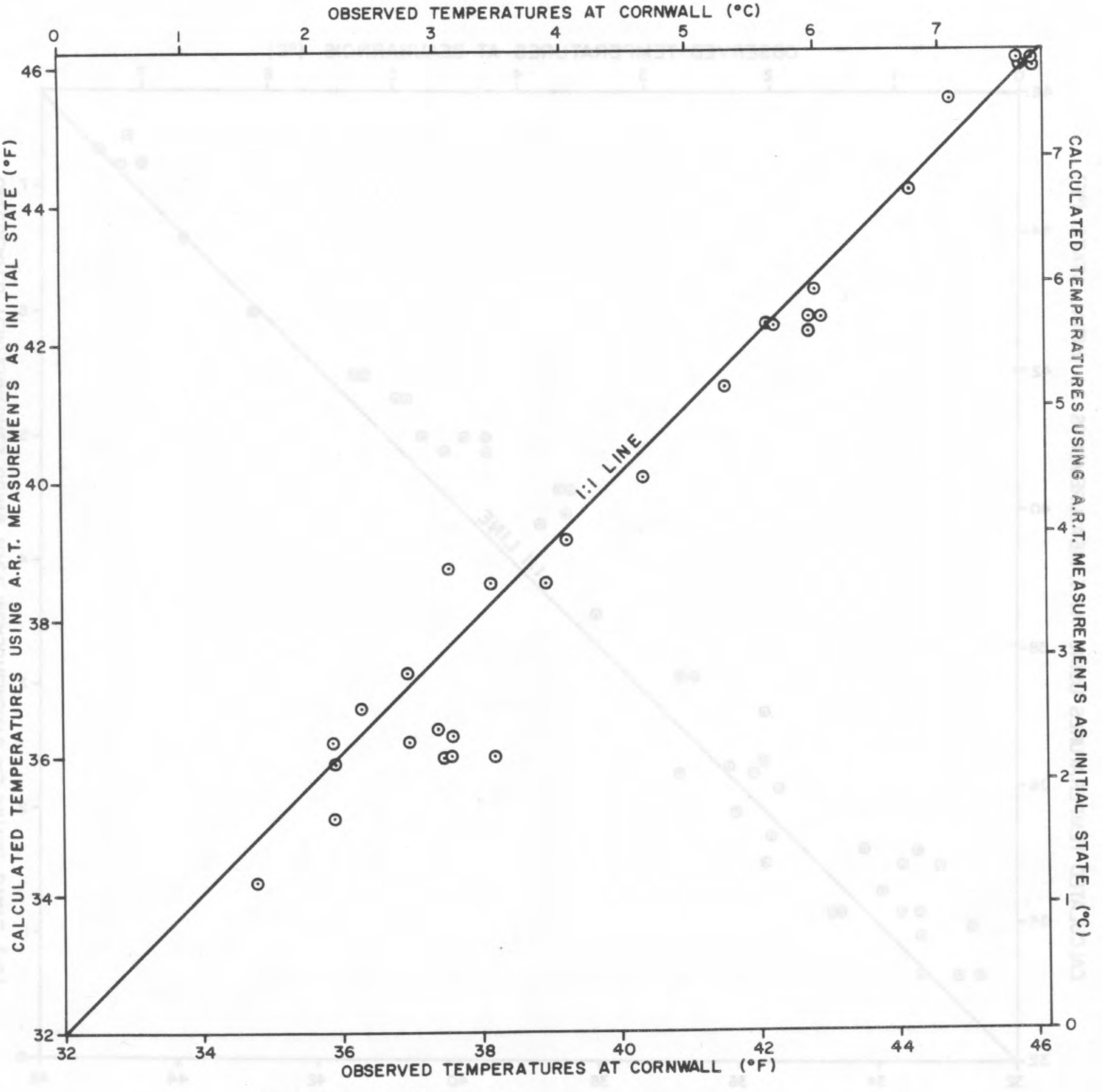


FIGURE 3

PLOT OF CALCULATED WATER TEMPERATURES USING A.R.T. MEASUREMENTS AS INITIAL STATE VS OBSERVED WATER TEMPERATURES AT BEAUHARNOIS

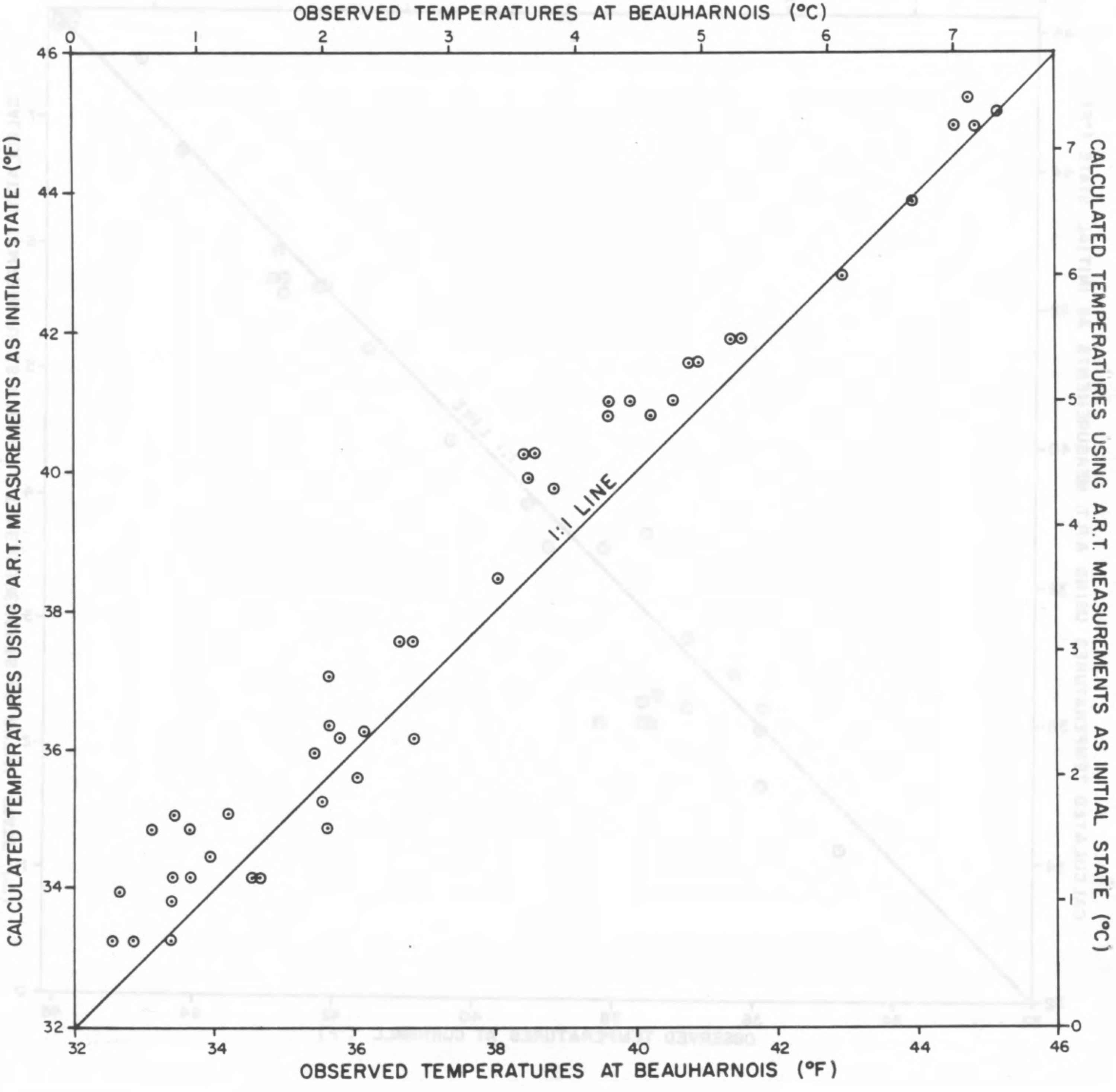


FIGURE 4

PLOT OF CALCULATED TEMPERATURES USING A.R.T. MEASUREMENTS AS INITIAL STATE

VS

OBSERVED TEMPERATURES AT

ICE STRUCTURE (LAPRAIRIE BASIN)

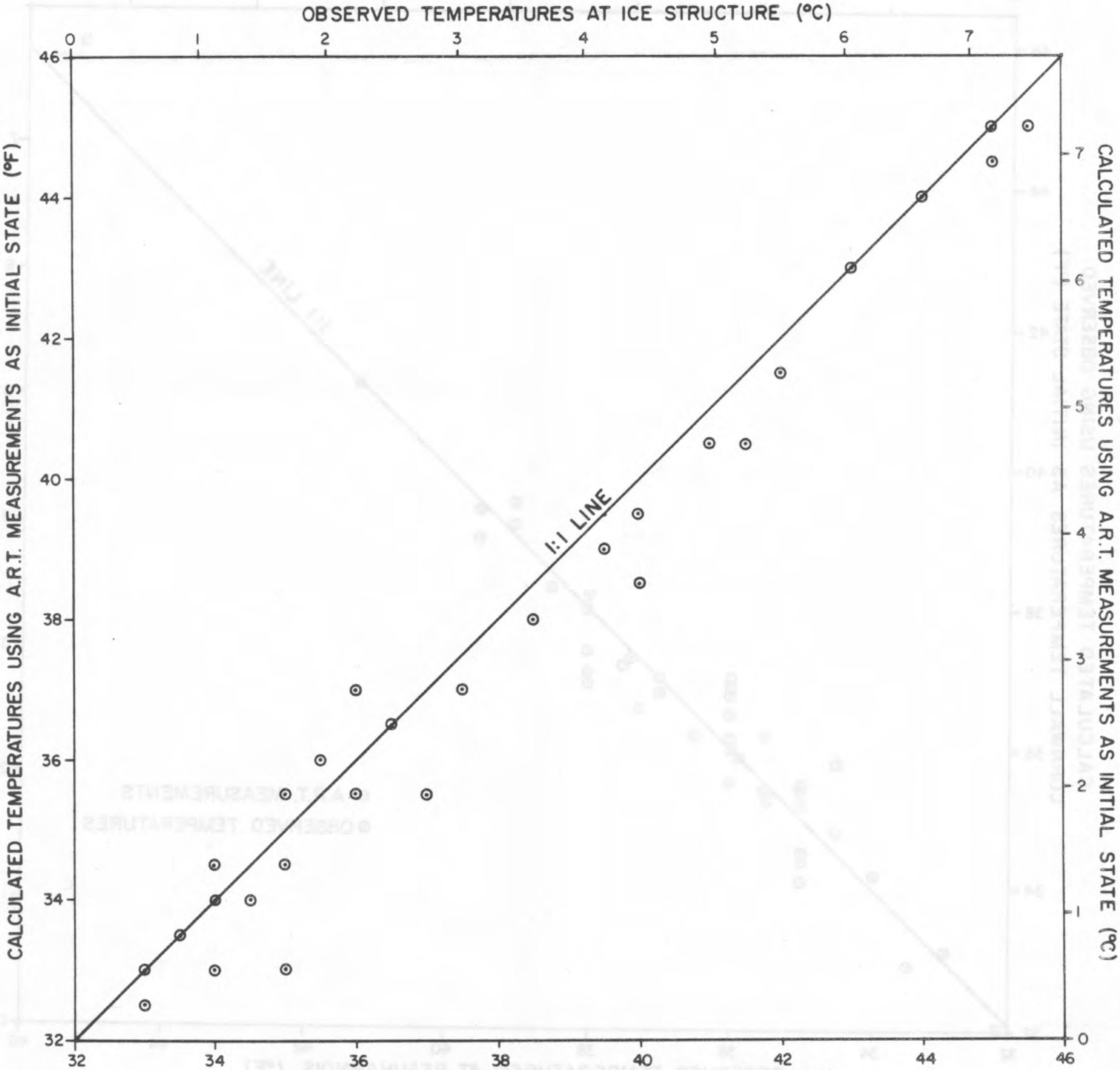


FIGURE 5

PLOT OF CALCULATED TEMPERATURES
USING OBSERVED CORNWALL TEMPERATURES
AS INITIAL STATE

VS

OBSERVED TEMPERATURES AT BEAUHARNOIS

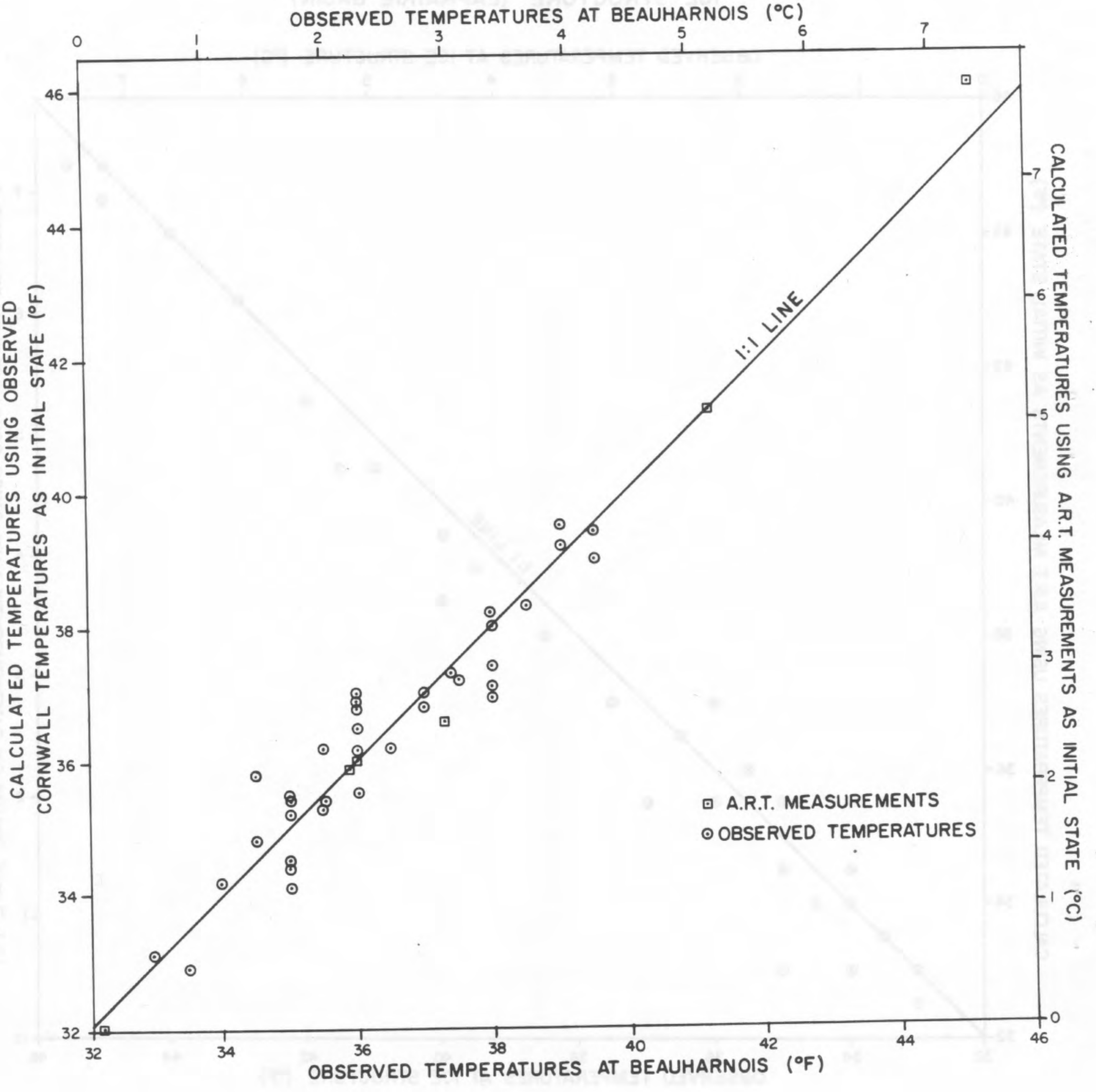


Figure 6 shows the results of the use of the model over both time and distance. Initial temperatures on November 17 and 25 and December 4, 12 and 30, at the left-hand side of the figure, are those determined from the ART flights in 1969. The traces show the calculated water surface temperature decline caused by the heat loss in both time and distance from Lake Ontario. Actual measured water surface temperatures at Cornwall, Beauharnois, Montreal and Sorel are plotted for the dates on which temperatures were calculated.

The results of these studies indicate that it is possible, with the use of the model along with known initial water temperatures, river discharge and air temperatures at various meteorological stations, to calculate water surface temperatures between Kingston and Lake St. Peter within 1°Fahrenheit. With the desire of power and navigation interests along the St. Lawrence River to have some advance knowledge as to when freeze-up might occur, it was decided to investigate the possibility of forecasting water surface temperatures from which freeze-up at Montreal, Beauharnois and Cornwall may be inferred.

DEVELOPMENT OF FORECAST PROCEDURES

The first step in developing a method of forecasting water surface temperatures was to test the adequacy of the model using recorded data over the test period (1959-1968). The input data consisted of actual daily mean temperatures at several meteorological stations along the St. Lawrence River together with recorded monthly mean river discharges and elevations. Since no recorded water surface temperature values were available for Kingston, Lake Ontario surface water temperatures as presented by Richards and Irbe(4) were selected for this study. As it was necessary to have initial water surface temperatures on successive days after the beginning of the forecast period, a normal temperature decline, determined from the above data, was used. Using the model and the input data described above, water surface temperatures were determined for successive days until such time as 32°F (inferred freeze-up) was reached at Montreal, Beauharnois and Cornwall. Forecasts were made beginning on 1 November, 16 November, 1 December and 16 December using the water surface temperature determined for these dates as the initial state condition. The following tabulations compare the observed and computed dates of freeze-up at Montreal, Beauharnois and Cornwall. The observed freeze-up dates were determined from the records of the St. Lawrence Seaway Authority and Hydro Quebec and may vary with the observers interpretation of freeze-up. The computed date of freeze-up is defined as the date on which the water surface temperature falls below 32.5°F.

It should be noted that the tabulations do not include computed dates of freeze-up at Montreal for forecasts beginning 1 and 16 December and at Beauharnois and Cornwall for forecasts beginning 16 December. This is due to the fact that heat loss in the river at these dates has been computed to be sufficient to indicate freeze-up has already taken place at these locations.

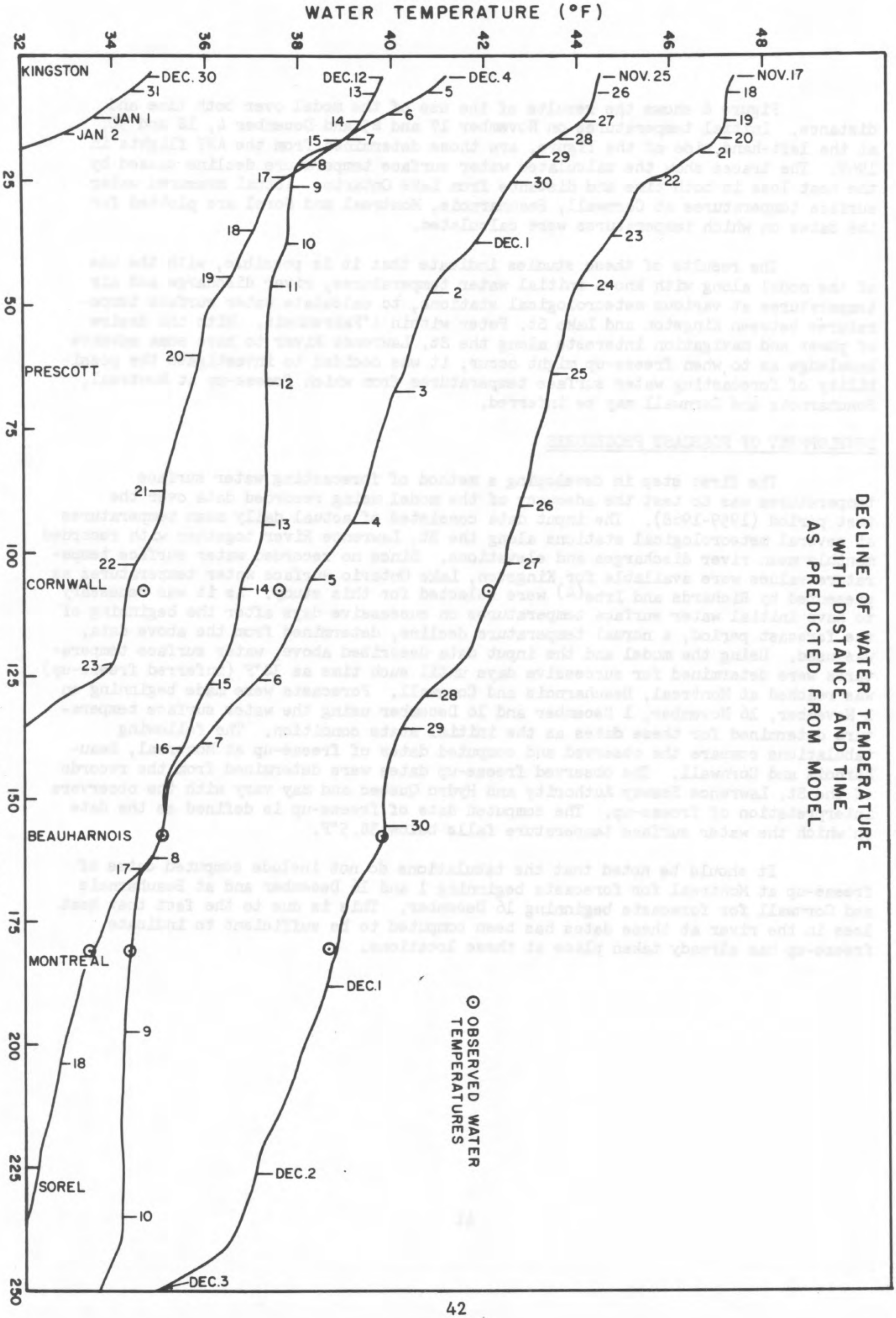


FIGURE 6

DECLINE OF WATER TEMPERATURE WITH DISTANCE AND TIME AS PREDICTED FROM MODEL

TABLE 1

COMPARISON OF OBSERVED AND COMPUTED DATES OF FREEZE-UP AT MONTREAL

Year	Observed Freeze-up Date	Computed Freeze-up Date Forecast Beginning 1 November	16 November
1959	Dec. 2	Dec. 22	Dec. 21
1960	11	13	13
1961	17	20	20
1962	14	16	15
1963	14	13	13
1964	3	7	7
1965	20	21	20
1966	17	21	24
1967	28	27	28
1968	10	17	11
Average	Dec. 14	Dec. 18	Dec. 17
Standard deviation (days)		7.1	6.6

TABLE 2

COMPARISON OF OBSERVED AND COMPUTED DATES OF FREEZE-UP AT BEAUHARNOIS

Year	Observed Freeze-up Date	Computed Freeze-up Date Forecast Beginning 1 November	16 November	1 December
1959	Dec. 21	Dec. 22	Dec. 21	Dec. 22
1960	9	13	13	-
1961	19	23	23	Dec. 23
1962	20	16	16	-
1963	15	14	14	-
1964	18	17	17	-
1965	20	22	21	Dec. 22
1966	24	24	25	25
1967	30	29	28	Jan. 1
1968	17	17	17	Dec. 17
Average	Dec. 19	Dec. 20	Dec. 20	
Standard deviation (days)		2.4	2.4	

TABLE 3

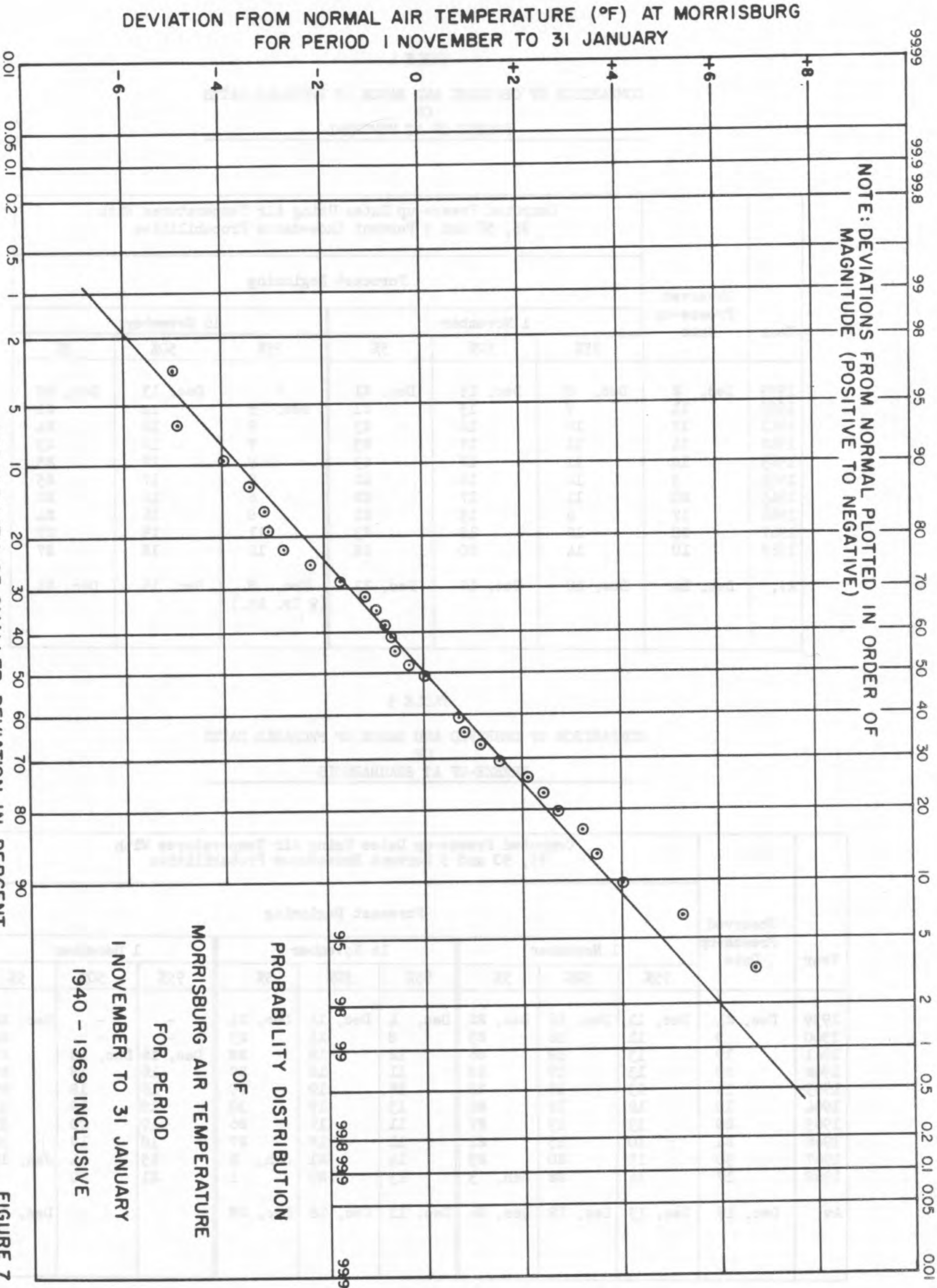
COMPARISON OF OBSERVED AND COMPUTED DATES OF FREEZE-UP AT CORNWALL

Year	Observed Freeze-up Date	Computed Freeze-up Date Forecast Beginning 1 November	16 November	1 December
1959	Dec. 20	Dec. 23	Dec. 22	Dec. 22
1960	24	14	14	15
1961	Jan. 4	26	26	25
1962	Dec. 22	21	21	21
1963	17	17	17	17
1964	Jan. 3	Jan. 12	Jan. 12	Jan. 12
1965	9	12	8	12
1966	Dec. 26	Dec. 24	Dec. 26	Dec. 27
1967	Jan. 2	Jan. 2	Jan. 2	Jan. 2
1968	Dec. 26	Dec. 26	Dec. 26	Dec. 26
Average	Dec. 28	Dec. 27	Dec. 27	Dec. 27
Standard deviation (days)		5.3	5.2	5.3

The results indicate that at Beauharnois and Cornwall, freeze-up dates as determined by the model generally occur within 2 to 3 days of the observed freeze-up dates. The larger discrepancies may be attributed to either incorrect estimates of initial water surface temperature or in the observed date of freeze-up. However, it is believed that the results obtained verify that the model produces adequate results considering the accuracy of the input data used. The results also indicate that, on the average, freeze-up occurs at Montreal four days prior to the computed date of freeze-up. This may be due to the fact that a considerable volume of colder water from the Ottawa River basin is contributed to the St. Lawrence River above Montreal and may be a factor in advancing the actual date of freeze-up.

The forecast of water surface temperatures first requires the forecast of air temperatures. Since reliable long-term forecasts were not available, the next step in the study was the development of air temperature regimes which could be expressed in terms of probabilities. Using daily mean air temperatures at several stations along the St. Lawrence River, probability distributions of the deviation from the long-term (1940-1969) temperature were derived for varying forecast periods. Figure 7 shows such a distribution for the forecast period 1 November to 31 January. The sum of the desired probability deviation and the long-term daily mean air temperatures provided temperature regimes with the desired exceedance probabilities. The use of the model and air temperatures with 5, 50 and 95 percent exceedance probabilities provided probabilistic forecasts of water surface temperatures. As before, the water surface temperatures were determined for successive days until such time as freeze-up was inferred at Montreal, Beauharnois and Cornwall. Tables 4, 5 and 6 compare the observed and probable range of freeze-up dates for the test period (1959-1968) at these locations.

An analysis of the results presented in these tables indicates the range in time in which ice formation may be expected to begin. Using air temperatures with exceedance probabilities of 95 and 5 percent over the period tested, freeze-up could be expected to occur at Montreal over a period of 13 days for forecasts beginning on 1 November, and 16 days for forecasts beginning 16 November. The range in time in which freeze-up may be expected to occur at Beauharnois is 13 and 17 days respectively for forecasts beginning 1 November and 16 November, and similarly for



PROBABILITY DISTRIBUTION
OF
MORRISBURG AIR TEMPERATURE
FOR PERIOD
1 NOVEMBER TO 31 JANUARY
1940 - 1969 INCLUSIVE

FIGURE 7

TABLE 4

COMPARISON OF OBSERVED AND RANGE OF PROBABLE DATES OF FREEZE-UP AT MONTREAL

Year	Observed Freeze-up Date	Computed Freeze-up Dates Using Air Temperatures With 95, 50 and 5 Percent Exceedance Probabilities					
		Forecast Beginning					
		1 November			16 November		
		95%	50%	5%	95%	50%	5%
1959	Dec. 2	Dec. 8	Dec. 15	Dec. 21	-	Dec. 13	Dec. 20
1960	11	7	15	21	Dec. 5	14	21
1961	17	10	16	23	9	16	24
1962	14	11	17	23	7	16	23
1963	14	11	17	23	9	17	25
1964	3	10	16	22	9	17	25
1965	20	11	17	22	6	16	22
1966	17	6	15	21	8	16	24
1967	28	12	18	23	11	19	27
1968	10	14	20	28	12	18	27
Av.	Dec. 14	Dec. 10	Dec. 17	Dec. 23	Dec. 8 (9 Yr. Av.)	Dec. 16	Dec. 24

TABLE 5

COMPARISON OF OBSERVED AND RANGE OF PROBABLE DATES OF FREEZE-UP AT BEAUHARNOIS

Year	Observed Freeze-up Date	Computed Freeze-up Dates Using Air Temperatures With 95, 50 and 5 Percent Exceedance Probabilities								
		Forecast Beginning								
		1 November			16 November			1 December		
		95%	50%	5%	95%	50%	5%	95%	50%	5%
1959	Dec. 21	Dec. 11	Dec. 16	Dec. 22	Dec. 4	Dec. 14	Dec. 21	-	-	Dec. 24
1960	9	11	16	23	8	15	23	-	-	24
1961	19	13	18	26	12	18	28	Dec. 16	Dec. 18	28
1962	20	13	19	28	11	18	27	16	18	29
1963	15	13	19	28	12	19	29	16	18	29
1964	18	12	18	26	13	19	30	18	19	31
1965	20	13	19	27	11	17	26	19	20	31
1966	24	10	15	21	11	17	27	18	19	30
1967	30	15	20	29	14	21	Jan. 2	25	24	Jan. 10
1968	17	16	22	Jan. 3	13	20	1	21	20	6
Av.	Dec. 19	Dec. 13	Dec. 18	Dec. 26	Dec. 11	Dec. 18	Dec. 28			Dec. 30

Cornwall, 18 and 22 days. The results also indicate that, on the average, freeze-up dates computed using temperatures with a 50 percent exceedance probability (long-term daily means) compare favourably with the observed dates of freeze-up.

A further test was carried out to determine if forecasts of water surface temperatures, more accurate than those computed using long-term daily mean air temperatures (50 percent exceedance probability), could be realized. The United States Weather Bureau provides a 30-day forecast of air temperatures which range from much above to much below normal for the period. These values, when used in conjunction with the long-term daily mean air temperatures, provided another forecast of air temperatures from which freeze-up dates could be determined. However, the freeze-up dates computed using this air temperature regime, showed little or no improvement over those computed using the long-term daily mean air temperature (50 percent exceedance probability).

CONCLUSIONS

The results of this study verify that the model developed to determine the heat loss in the Kingston to Cornwall reach of the St. Lawrence River may be applied to the reach of the river extending to Lake St. Peter. Using the ART data as the initial state condition, the results shown on Figures 2 through 5 indicate that water surface temperatures can be estimated within 1°Fahrenheit. The accuracy obtained is of an order of magnitude similar to the accuracy of the ART measurements.

The accuracy in forecasting water surface temperatures is necessarily dependent upon the accuracy of the air temperature forecasts. Probabilistic forecasts of water surface temperatures give an indication of the earliest and latest dates of freeze-up at Montreal, Beauharnois and Cornwall. For example, Table 6 shows that for the forecast beginning 1 November 1967, there is only a 10 percent chance that the 32° isotherm will reach Cornwall before 21 December 1967, or after 10 January 1968, with the most probable date of freeze-up being 29 December 1967. Forecasts of this nature will permit the navigation and power interests to determine the risk they are taking with respect to scheduling of ship movements and closure of ice booms.

From the results of the study, it appears that useful forecasts of water surface temperatures, from which freeze-up dates on the St. Lawrence River can be inferred, are practicable. The ART provides economical operational data of the initial state of the river from which forecasts can be made. The use of currently available monthly forecasts of levels and flows combined with the ART data and forecasts of air temperature, will provide the necessary data for forecasting water surface temperatures.

ACKNOWLEDMENT

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TABLE 6

COMPARISON OF OBSERVED AND RANGE OF PROBABLE DATES
OF
FREEZE-UP AT CORNWALL

Year	Observed Freeze-up Date	Computed Freeze-up Dates Using Air Temperatures With 95, 50 and 5 Percent Exceedance Probabilities								
		Forecast Beginning								
		1 November			16 November			1 December		
		95%	50%	5%	95%	50%	5%	95%	50%	5%
1959	Dec. 20	Dec. 15	Dec. 22	Dec. 31	Dec. 11	Dec. 18	Dec. 26	-	Dec. 20	Dec. 31
1960	24	16	22	Jan. 1	13	20	29	-	20	Jan. 1
1961	Jan. 4	19	25	8	18	25	Jan. 9	Dec. 16	24	8
1962	Dec. 22	20	28	9	17	24	9	16	24	9
1963	17	20	27	9	20	27	12	16	24	9
1964	Jan. 3	18	25	8	19	27	11	18	27	12
1965	9	20	26	8	16	23	7	19	28	11
1966	Dec. 26	14	20	Dec. 28	17	24	9	18	26	11
1967	Jan. 2	21	29	Jan. 10	21	Jan. 2	14	25	Jan. 9	31
1968	Dec. 25	25	Jan. 8	15	21	2	12	21	2	13
Av.	Dec. 28	Dec. 19	Dec. 26	Jan. 6	Dec. 17	Dec. 25	Jan. 8		Dec. 27	Jan. 10