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Effects of Spring Breakup on Microscale Air Temperatures in the Mackenzie River Delta

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ABSTRACT. The effects of spring breakup on microscale air temperatures in the Mackenzie River delta were investigated by means of intervention analysis. Small but statistically significant increases in temperatures were detected for some areas within the delta and appeared to be related to ice breakup events in nearby channels and lake systems. The magnitude of the temperature increase appeared to be correlated with the severity of winter conditions preceding breakup and with the rate at which breakup progressed. The relative importance of changes in surface albedo and river heat input in causing air temperature rises is discussed. Temperature increases due to breakup are small in comparison to seasonal warming trends and diurnal temperature fluctuations.

Key words: Mackenzie River, delta, breakup, climate, air temperature, intervention analysis, time-series

RÉSUMÉ. Les effets de la débâcle printanière sur les températures microclimatiques de l'air observées dans le delta du fleuve Mackenzie ont été étudiés par une analyse d'intervention. Des augmentations de température minimes mais néanmoins statistiquement significatives furent détectées dans certaines régions du delta et semblent êtres apparentées aux évenements de la débâcle se produisant dans les systèmes avoisants de canaux et de lacs. L'amplitude des augmentations de température semble varier en fonction de la sévérité des conditions hivernales précédant la débâcle et en fonction de la vitesse avec laquelle la débâcle s'est produite. L'importance relative des changements de l'albedo superficiel et de l'apport calorifique des eaux fluviales est aussi discutée. Les augmentations de température résultant des phénomènes associés à la débâcle sont minimes quand compareés aux réchauffement saissonier et aux fluctuations diurnales de température.

Mots clés: Fleuve Mackenzie, delta, débâcle, climat, température de l'air, analyse d'intervention, séries chronologiques

Traduit par Dr. Louise Goulet.

INTRODUCTION

The spring breakup period represents a period of major transition in the energy balance within the Mackenzie delta (Abrahamsson, 1966). During winter, net radiation is negative owing to the short arctic day and the high albedo of the snow- and ice-covered terrain (Burns, 1973). Air masses are relatively stable. Energy input to the atmosphere from water bodies is zero owing to ice and snow cover. In summer, net radiation received is considerably greater because of the long days and the low albedo of the dark vegetation and turbid water. During breakup, a sharp transition in energy balance takes place as surface albedo changes from 70-85% to 10-20% with the flooding of snow- and ice-covered terrain, lakes, and channels by sediment-laden water, and solar radiation received at the surface increases rapidly (Burns, 1973). Abrahamsson (1966) notes that temperature increase along the Yukon coast is rapid during the pre-breakup period, and averages 9.5°C in March-April, 13.5°C in April-May, and 7.5°C in May-June. Mean monthly and daily temperatures are variable along the coast and in the delta during the spring transition period. Breakup generally occurs about one week after the threshold value of 0°C has been reached (Abrahamsson, 1966).

MacKay and MacKay (1974) document the importance of warm Mackenzie River water as a major source of energy into the delta during the breakup period. Findlay (1981), using MacKay and MacKay's (1974) data, has computed total river energy input to the delta to go from zero in April to 235×10^9 megajoules (MJ) in May to 245×10^9 MJ in June. Total river energy input to the delta during June is roughly equal to total net radiation input. Water temperatures as high as 9°C have been recorded in Middle Channel behind the edge of fractured ice (S.P. Blachut, B.C. Hydro, pers. comm. 1981). Large amounts of heat energy are taken up by melting ice in the channels and lakes during this period.

Gill (1971a, 1971b, 1973, 1975, 1977) refers repeatedly to the importance of sudden surface albedo changes and ice flushing, both resulting from spring flooding, as being significant in causing a rapid increase in delta mesoscale air temperatures. However, the only quantitative evidence he presents for such localized climatic effects is a difference in mean leaf lengths of willow (*Salix alaxensis* (Anderss.) Cov.) growing within and near the delta (Gill, 1975). Despite the lack of critical testing of the hypothesis that albedo change during breakup is a significant factor, recent literature (e.g. Findlay, 1981; Peterson *et al.*, 1981) has continued to assign it a very prominent role.

Microclimates in the delta are subject to rapid and variable changes during breakup. Shoreline climates are most susceptible to the influx of warmer flood waters and the effects of increasing radiation absorption as snow and ice are submerged and flushed by sediment-laden water. Shoreline vegetation types such as *Equisetum*, *Salix* and *Carex* probably have the most changeable bioclimates during breakup. Forest types such as *Picea*, located on higher levels and delta plains, are probably subjected to lower amounts of change, although no area within the delta is farther than a few hundred metres from a water surface. Because of the mosaic of land/water interfaces and vegetative cover types, and the relatively rapid movement of arctic advective air currents across the delta surface, the micrometeorological temperature and humidity gradients are probably highly complex.

Two approaches to studying the local temperature changes

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during breakup may be considered. Ambient temperature is one of the most important limitations on plant growth in subarctic regions (Bliss, 1962; Savile, 1972). A series of observations on phenological changes during breakup could be compared to similar observations on vegetation close to the delta but distant from the climatic effects of breakup. Alternatively the effects of breakup on air temperatures in the vicinity of lakes and channels over time can be examined and analyzed by various means, including the use of intervention analysis.

Intervention analysis is an adaptation of time series analysis (Box and Jenkins, 1970) which provides for modelling of data which are sequential and autocorrelated. It is useful for distinguishing between transient and permanent effects. An "intervention" is defined as a natural or man-induced event which affects the time series data. In this study the intervention would be some phase of the breakup process which affects the energy budget and consequently the sequential air temperature series. Intervention analysis has been used on air pollution and economic data (Box and Tiao, 1975), on hydrological data (Hipel *et al.*, 1975, 1978; Lettenmaier *et al.*, 1978), and on physiological data (Thompson *et al.*, 1982).

METHODS

Several sets of data on breakup and air temperature changes were utilized. In 1981 and 1982 thermographs were installed and maintained in three locations in the delta (Fig. 1). Thermograph locations corresponded roughly to "southern", "middle", and "northern" delineations of the modern delta. Thermographs were mounted approximately 115 cm above ground level within standard Stevenson screens. Sites were not cleared and the thermographs recorded air temperatures within natural *Picea* (Area 1, Middle Channel) or *Salix* (Area 5) communities. Air temperatures served as indices of microscale energy conditions before, during, and after breakup. Data were collected every four hours from the time of installation, generally mid- to late April, until the end of June. This period provided sufficient data points before and after the breakup events for intervention analysis. Data sequences were assembled from all three stations in 1981 but only from Middle Channel in 1982 due to flood damage to equipment at the other sites. Dates of breakup events such as open leads and surface flooding were taken from personal records and field notes of other observers in the area (S.P. Blachut, B.C. Hydro, pers. comm. 1981, 1982; D.S. McLennan, L.D. Cordes Associates, pers. comm. 1982).

Daily maximum and minimum air temperatures were collected in Aklavik from 1956 through 1960 (Atmospheric Environment Service, 1956-1960). Thermographs were located in a cleared site within a few hundred metres of West Channel. Data on spring breakup were recorded by the RCMP and the local Catholic and Anglican missions (J.R. Mackay, University of B.C., pers. comm. 1981). These data consisted of dates of "first movement" of river ice, presumably when flood stages first began lifting the ice cover, and dates of "ice out", i.e. when fractured ice was flushed through the channel. Aklavik is only 9 m above mean sea level and thus less than 9 m above channel water levels, therefore any significant temperature effects due to the breakup process would have been measured by thermographs within the standard Stevenson screens.

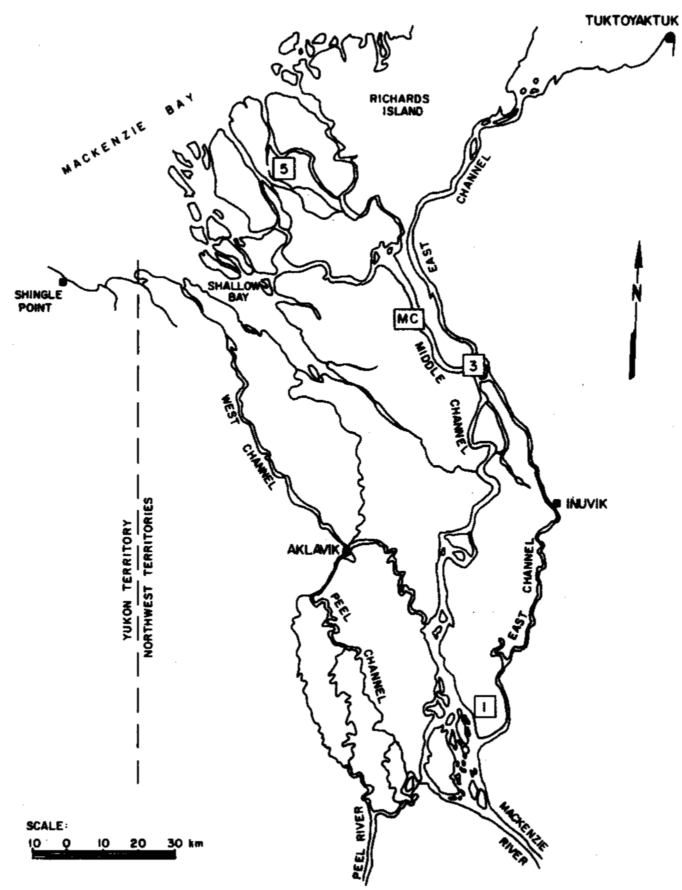

FIG. 1. Mackenzie River delta, showing locations of installed thermographs (open squares) and AES weather stations (solid squares).

An additional set of hourly temperature data (C.P. Lewis, Inuvik Scientific Resources Centre, pers. comm. 1981) was recorded by a thermograph within a *Picea* community in Study Area 3 (Fig. 1) in 1969. Records of ice breakup progression in the adjacent channel and lakes included first occurrence of open leads and lake flooding, and progression of ice flushing and melting.

The time series data were analyzed by an adaptation of the model developed by Box and Tiao (1975) and described by Lettenmaier *et al.* (1978).

$$Y_t = w_0 + \frac{w(B)}{d(B)} S_T(t) + \frac{\Theta(B)}{\Phi(B)} a_t$$

where Y_t is a datum (= temperature) observation at time t with time increments between t and t+1 constant (daily, hourly, or 4-hourly in this study), w_0 is the process base level, $S_T(t)$ is a function representing the intervention occurring at t=T, a_t is the error term with a Gaussian probability distribution, a mean of zero and a constant variance σ^2, and w(B), d(B), Θ(B), and Φ(B) are autoregressive polynomials using the backshift operator B (Box and Tiao, 1975).

Considering the advective movement of air masses over the delta surface (Abrahamsson, 1966; Burns, 1973), it can be hypothesized that the process base level (w_0) for air temperatures measured within the delta is some function of temperatures measured on the periphery. This was confirmed by the high linear correlations (r always >0.95, P always <0.001) between temperatures measured at sites in the delta and those from the coastal stations at Shingle Point and Tuktoyaktuk. Since breakup within the delta occurs in advance of any similar event at Tuktoyaktuk or Shingle Point (Allen, 1977), the data from these stations would represent the process base level, but would not include the intervention effect due to breakup within the delta.

For the Aklavik data, the process base level in the time series model was taken to be the temperature measured at Shingle Point on the same date. Daily maximum and minimum temperatures were analyzed separately. A fitting coefficient was computed by ordinary least squares regression. No data were available from Shingle Point in 1956 and 1957, and for these years lag-one Markov models (Lettenmaier *et al.*, 1978) were examined. Very poor data fits were found, and these two years were later abandoned for the purposes of this study.

For the remaining data a slightly more complex model was used. Because data were collected hourly or 4-hourly, the time series was much longer. This was an advantage since intervention analysis is more efficient when sample size is at least 100 and preferably greater (Lettenmaier *et al.*, 1978). However, the data tended to oscillate due to diurnal periodicity, and a sine function was added to account for this. An additional term was included to account for possible interaction between the sine function and the base process temperature (i.e., hypothesizing that diurnal amplitude changes as the general temperature increases through the season).

From the inspection of the data plots, the intervention term $S_T(t)$ was taken to be a simple step function in all cases, and hence could be expressed as $w_1 S_T(t)$ (Lettenmaier *et al.*, 1978). For most data sets the date of intervention was somewhat arbitrarily selected as the time when a major breakup event occurred, usually gross channel or lake flooding ("first movement" of river ice in the case of the Aklavik data). S_T was set equal to 0 for all dates prior to this date and equal to 1 thereafter.

The autoregressive error component has been modelled in several ways (Box and Tiao, 1975; McLeod *et al.*, 1977; Hipel *et al.*, 1978). The method adapted here was available through the AUTOREG procedure (SAS Institute, 1979) as derived from Box and Jenkins (1970) and Johnston (1972).

$$\frac{\Theta(B)}{\Phi(B)}\, a_t = a_t - \Psi_1 a_{t-1} - \Psi_2 a_{t-2} - \cdots - \Psi_q a_{t-q}$$

where the left-hand term is as defined earlier and $\Psi_1 \ldots \Psi_q$ are autoregressive coefficients of order q. The closeness of the data fits was checked in each case by plotting residuals against predicted values and against time. Temperatures measured during spring are indicative of a general warming trend and hence do not constitute a stationary time series over that period. However, examination of residuals following regression on temperatures from a peripheral delta station, or on a sine function to allow for diurnal fluctuation, indicated constant means and variances for the pre- and post-breakup periods, and the requirements for stationarity were therefore assumed to have been met.

RESULTS

Tables 1 and 2 summarize the pertinent data on breakup/air temperature relationships for the thermograph stations. Tables 3 and 4 present the pertinent data on the intervention analyses. Intervention coefficients varied from −1.1 to 5.1. Seven of 11 coefficients computed with models using peripheral delta (Shingle Point or Tuktoyaktuk) temperatures as the base process level were statistically different from zero ($p<0.05$). Temperatures at the delta thermographs for the April-June period closely followed those recorded at the peripheral stations (Fig. 2). There was significant autocorrelation in most of the temperature series although sometimes only of the first order. Autoregression was not significant ($p \geq 0.05$) for $q \geq 4$, except for the hourly series from Area 3 where $q=24$ was significantly different from zero ($p<0.05$). No significant relationship between diurnal temperature amplitude changes and daily mean temperatures was detected.

Since the intervention was in effect modelled as a single dummy variable set equal to unity, the intervention coefficients in Tables 3 and 4 represent estimates of the mean rise (or fall) in the temperatures over the time span when the intervention was present. The largest temperature increases (approximately 5°C) associated with breakup were detected for the Middle Channel thermograph in 1982 and the Aklavik thermograph in 1958. Smaller but statistically significant rises were detected for the thermograph in the outer delta in 1981 and for Aklavik in 1959 and 1960.

The differences between 1981 and 1982 breakups were significant in several respects. In 1982, breakup was a fairly rapid event with little prior deterioration of ice and snow

TABLE 1. Breakup progression near thermographs within the Mackenzie delta

		First open leads			Intervention date			Channel/lake ice clear		
Thermograph	Year	Date	Max. temp.	Min. temp.	Date	Max. temp.	Min. temp.	Date	Max. temp.	Min. temp.
Middle Channel	1981	18 May	12	1	20 May	10	−1	29 May	10	5
Middle Channel	1982	18 May	3	−2	20 May	3	−4	27 May	3	−4
Area 1	1981	16 May	6	−6	22 May	11	0	31 May	2	0
Area 5	1981	24 May	3	−1	24 May	3	−1	27 May	3	−1
Area 3[1]	1969	7 May	4	−5	9 May	2	−1	5 June	−2	−6

[1]Data from C.P. Lewis, Inuvik Scientific Resources Centre.

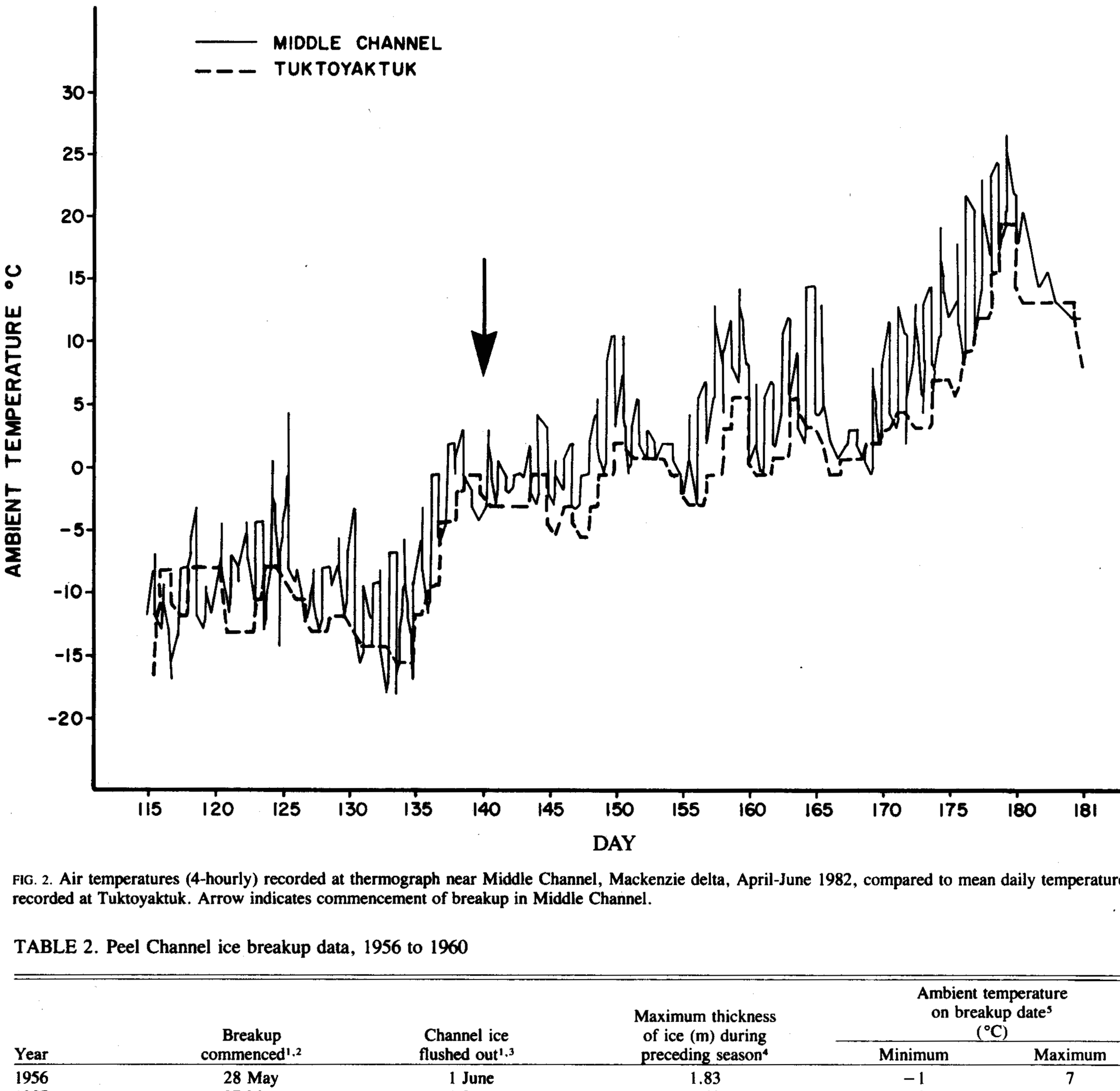

FIG. 2. Air temperatures (4-hourly) recorded at thermograph near Middle Channel, Mackenzie delta, April-June 1982, compared to mean daily temperatures recorded at Tuktoyaktuk. Arrow indicates commencement of breakup in Middle Channel.

TABLE 2. Peel Channel ice breakup data, 1956 to 1960

Year	Breakup commenced[1,2]	Channel ice flushed out[1,3]	Maximum thickness of ice (m) during preceding season[4]	Ambient temperature on breakup date[5] (°C)	
				Minimum	Maximum
1956	28 May	1 June	1.83	−1	7
1957	27 May	1 June	1.52	−3	5
1958	25 May	—	1.50	−2	6
1959	5 June	—	1.65	−3	6
1960	29 May	30 May	—	0	7

[1]Data from J.R. Mackay, Department of Geography, University of British Columbia.
[2]Date when ice was first observed cracking and moving.
[3]Date when major ice floes flushed out of channel.
[4]Data from Allen (1977).
[5]Data from Atmospheric Environment Service (1956-1960).

cover, and with peak inundation of the delta surface varying from 90 to 100%. The mean daily temperature recorded at the Middle Channel thermograph during 1-20 May was −7.1°C. The computed intervention coefficient for the Middle Channel temperature series was 5.0, significantly different from zero ($p<0.001$). By contrast, the 1981 breakup was a more gradual event, with extensive deterioration of ice and snow cover prior to breakup and peak inundation at the delta surface varying from 30 to 60% across the southern and central delta (R.E. Taylor, B.C. Hydro, pers. comm. 1981). The intervention coefficients and the mean daily temperatures for the three-week period preceding intervention for the three 1981 temperature series were 0.7 and −0.5°C for Middle Channel, −0.2 and 2.3°C for Area 1, and 1.6 and −1.6°C for Area 5 respec-

TABLE 3. Parameters of intervention models used on ambient temperature hourly and 4-hourly series

Thermograph	Year	Intervention: Coefficient	Standard deviation	Probability that coefficient=0	Autoregression model: Base process variable	R^2	MSE	d.f.
Middle Channel	1981	0.7	0.5	0.21	Tuktoyaktuk Daily Mean	0.69	5.1	201
Middle Channel	1982	5.0	1.1	<0.001	Tuktoyaktuk Daily Mean	0.51	4.5	391
Area 1	1981	−0.7	0.6	0.26	Tuktoyaktuk Daily Mean	0.56	7.0	138
Area 5	1981	1.6	0.7	0.03	Tuktoyaktuk Daily Mean	0.46	6.8	170
Area 3	1969	−0.2	0.8	0.80	Tuktoyaktuk Daily Mean	0.63	22.1	1508

TABLE 4. Parameters of intervention models used on ambient temperature daily series (Aklavik thermograph)

Year	Maximum or minimum daily temperature series	Intervention: Coefficient	Standard deviation	Probability that coefficient=0	Autoregression model: Base process variable	R^2	MSE	d.f.
1958	Maximum	5.1	1.8	0.006	Shingle Point daily maximum	0.77	17.5	88
1958	Minimum	4.4	1.3	<0.001	Shingle Point daily minimum	0.87	10.8	88
1959	Maximum	3.1	1.2	0.01	Shingle Point daily maximum	0.88	11.5	88
1959	Minimum	3.1	1.0	0.002	Shingle Point daily minimum	0.92	8.2	88
1960	Maximum	2.1	1.2	0.10	Shingle Point daily maximum	0.87	8.6	80
1960	Minimum	3.5	1.4	0.02	Shingle Point daily minimum	0.78	8.3	80

TABLE 5. Comparison of ambient temperatures with and without breakup effects near Mackenzie Delta thermograph sites

			Period following intervention		Recorded temperatures °C			Modelled temperatures °C: With intervention			Without intervention		
Thermograph	Year	Frequency	Dates	Days	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Middle Channel	1981	4-hourly	20 May - 30 June	42	4.8	−1.3	23.0	4.7	−1.1	20.8	4.5	−1.8	20.6
Middle Channel	1982	4-hourly	20 May - 30 June	42	6.5	−4.3	27.0	6.1	−4.5	24.5	4.8	−5.9	23.1
Area 1	1981	4-hourly	22 May - 30 June	40	10.9	0.0	15.0	10.7	0.0	13.8	10.9	−0.6	14.6
Area 5	1981	4-hourly	24 May - 30 June	38	6.7	−3.1	23.5	6.2	−3.3	21.8	5.5	−3.6	20.7
Area 3	1969	Hourly	9 May - 30 June	53	4.6	0.6	25.1	4.6	0.7	23.8	4.8	0.7	23.8
Aklavik	1958	Daily	25 May - 30 June	37	11.2	−2.2	27.2	10.9	2.0	24.9	6.7	−3.8	19.6
Aklavik	1959	Daily	5 June - 30 June	26	8.9	−3.3	23.3	8.4	−3.8	27.0	6.1	−5.2	23.2
Aklavik	1960	Daily	29 May - 30 June	33	9.3	−2.2	27.3	8.3	4.4	32.1	6.0	1.1	27.2

tively. Field observations confirmed that Area 5 in the outer modern delta had a more extensive ice and snow cover immediately prior to breakup than the areas farther south.

DISCUSSION

Intervention analyses of air temperature time series data for breakup periods in the Mackenzie delta indicate that rises in local air temperatures were sometimes associated with breakup. The effects were more marked for breakups following relatively colder late-winter periods and for those associated with higher discharges in either the Mackenzie or the Peel river. There is also some indication that intervention effects were more marked for breakup in larger channels (e.g. Middle and Peel channels) than for areas containing lakes and small channels systems. Incursion of flood waters and progression of breakup within distributary channels and lake systems occurs more gradually than within main channels.

Changes in air temperatures during the breakup period in some cases were not detectable at the level of the thermograph, i.e. 2-4 m above the water/land interface for the installed thermographs, and less than 9 m for the Aklavik station. Although the diurnal and other variation in the temperature data was one reason for not detecting the change, the study results suggest that advective air currents have an effect on energy balance at fairly low levels.

During May and June, radiation and the incursion of river heat are the major energy sources in the delta. The timing of one source relative to the other is highly variable, being determined by factors such as severity of winter conditions in the delta, velocities and temperatures of warmer advective air masses moving across the delta, and spring thaw temperatures and snowpack in the upper Mackenzie basin which in turn influence the discharges, temperatures, and timing of spring flood water which enters the delta. When spring floods enter the delta and surface conditions are characterized by low temperatures and extensive ice and snow cover (e.g. 1982), then local temperatures within the delta rise rapidly by as much as 5°C average (as suggested by the intervention analysis). When spring floods are lower, later, and possibly colder, and are preceded by a period of increasing radiation input and general warming (e.g. 1981), then local delta temperatures are affected relatively little, with no significant intervention effect. The frequencies of occurence of the various events are not easily established without long-term breakup and atmospheric data.

The intervention was modelled as a single step function (Lettenmaier *et al.*, 1978), the implication being that the intervention lasts until the end of the data series. This is probably at least partly valid for the temperature series used in this study since the intervention represents essentially the contribution of river energy which, during June, is approximately equal to the net atmospheric energy contribution (Findlay, 1981).

Although the air temperature changes due to breakup were found to be relatively small, the biological effects may be significant. Breakup occurs when the mean daily temperature is at or very close to 0°C which is approximately the time when leaf budding and other active plant growth has been observed to commence in the delta (D.S. McLennan, L.D. Cordes Associates, pers. comm. 1982). The effect of breakup would thus be to increase air temperatures by a small amount, but at a time when these temperatures are near a critical range for initiation of active plant growth.

Regardless of the timing of the initial energy contributions, it is apparent that within one to three weeks following breakup the biological significance of any intervention effect declines rapidly. Daily minimum air temperatures reach a level of about 10°C within this period, and the maximum intervention effect measured within vegetation communities near the channels is estimated to be closer to 5°C. Diurnal fluctuations and frequent advective changes (as indicated by temperature changes at Tuktoyaktuk, Shingle Point, and other peripheral stations) exceed the intervention effect within one to three weeks of breakup.

Gill (1971b, 1973, 1975, 1977) hypothesized that retardation of the spring breakup in the Mackenzie delta by impoundment of river flows would have significant effects on the bioclimate and the delta ecosystems. The time-series model used in this study provides a means of testing this hypothesis, simply by running the model for the same time period and deleting the intervention. Comparisons of the air temperatures with and without the intervention, and as actually recorded for the post-intervention period, are presented in Table 5. The differences between mean recorded temperatures and mean modelled temperatures (+ intervention) range from 0 to 1.0°C. The differences between mean modelled temperatures, with and without the intervention, range from −0.2 to 4.2°C. The range of temperatures (minimum to maximum) in the post-intervention period is similar in all groups.

The results suggest that total prevention of river energy input and resultant decrease in amounts of net radiation received by the delta surface in late May-June would lead to a smaller increase in microscale air temperatures than would occur under natural conditions. For the elevations at which temperatures were measured in this study, the differences between a natural and a modified breakup could vary from close to 0° to about 5°C. During this same period, diurnal and other fluctuations would cause the temperature to vary from as low as −6°C to as high as 27°C. Major river energy inputs to the delta could, in fact, only be prevented totally by a major impoundment of the Mackenzie River relatively close to the delta, e.g. at the Ramparts. Impoundment within the upper Mackenzie basin could lead to changes in extent and timing of flooding, but the primary effects of breakup, i.e. changes in surface albedo and incursion of warm water, would not be completely averted since tributary inflows below any such impoundment would continue. Although the bioclimatic effects from altered river heat inputs and surface albedo changes would likely be small and probably overshadowed by background variation, other physical effects of river regulation could be more significant. Breakup of the Beaufort Sea ice cover is seasonally affected by Mackenzie River discharges, and both the longevity and flushing of the ice cover could be influenced by regulation. The temperature of the advective air masses moving across the delta could thus be altered. These complex factors were outside the modest scope of this study, and would provide a basis for a further challenging study of river-ocean-climatic interactions.

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