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HYDROMETEOROLOGICAL ASPECTS OF ICE JAM FORMATION AT FORT MCMURRAY, ALBERTA

BY

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Abstract

The object of the present study was to determine which, if any, meteorological parameters could be used to forecast the physical characteristics of breakup on the Athabasca River at Fort McMurray, Alberta.

To this end, hydrological and meteorological data presumed relevant to breakup were collected from various sources, including the Water Survey of Canada, Atmospheric Environment Service, and breakup observer records. An examination of the various data revealed firstly that two meteorological variables: degree days of thaw and hours of bright sunshine, measured on a daily basis at Fort McMurray, could be used in the form of a regression equation to predict the discharge at breakup. As conventional discharge records are, during the several days prior to breakup, unreliable due to hydraulic disturbances generated upstream in the flow, the development of such a relation was a necessary first step to a meteorological description of maximum stage at breakup through the sole use of meteorological variables.

Secondly, it was assumed that the amount of solar-radiation absorbed by the river ice cover in a short period prior to breakup provided a measure of the strength of the ice at breakup, and that solar radiation was adequately described by the hours of bright sunshine accumulated over the same short period. Regression techniques were used to compare the estmated discharge at breakup and accumulated hours of bright sunshine prior to breakup, to observed values of the maximum breakup stage. Several relationships, both linear and non-linear were produced, with one non-linear model demonstrating the best correspondence with observed values. A maximum stage forecasting technique was developed for field use. It relied on four-day meteorological forecasts of cloud cover and temperature and was based on the best regression.

Thirdly, an attempt was made to estimate the time of breakup, through the examination of the meteoriogical variables used to estimate stage and discharge over different pre-breakup periods. The results were inconclusive.

Finally, the characteristics of the antecedent upper atmospheric synoptic pattern and flow above Fort McMurray were examined for any apparent connection to the timing and properties of breakup. Some indication of such connections existing were revealed, however the examination was of insufficient detail to be conclusive.

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CHAPTER 1

INTRODUCTION

Severe ice jams and their associated floods have caused property damage and, on occassion, loss of life. A 1952 ice jam flood on the Missouri River caused the deaths of 9 people, and property damage equivalent to about U.S. $ 450 million in current dollars (Carey et al, 1973). In New Brunswick's St. John River valley in 1976, two lives were lost and property damage and destruction was estimated to have cost more than $ 3.5 million (LeBrun- Salonen, 1983). The spring of 1987 saw extensive breakup flooding at the Town of Perth-Andover, sufficiently serious to require large scale evacuation, and resulting in the destruction of a railway bridge. Although such ice related floods in New Brunswick have constituted only 35 percent of the total number of floods, they have caused 70 percent of the flood damage. In the Soviet Union, ice related floods are said to "inflict tremendous losses on the national economy" (Sinotin et. al., 1973).

It is evident that, given an appropriate coincidence of certain ice, discharge and meteorological conditions, ice jams and ice jam floods can occur on virtually any river flowing in a temperate or cooler climatic zone. This would involve anywhere in the continental United States and Canada north of the 0° C isotherm, an area which includes more than two-thirds of North America (Carey, et. al, 1973) (Fig. 1).

Water levels resulting from ice jam floods can exceed those of even rare open water floods (Gerard, 1984). Andres and Doyle (1984) have, for example, shown for the Athabasca River at Fort McMurray that the presence of an ice jam can increase the open-water stage by as much as 5 m, resulting at times in a sudden and catastrophic inundation of sections of the townsite.

Ice jams can occur at both breakup and freezeup. Breakup ice jams are, however, more damaging and more difficult to predict. They are therefore the focus of this investigation. According to most investigators, the sequence of ice jam formation at breakup in a river is as follows. In the spring, with the onset of milder weather, the thawing of snow in the river basin begins and the discharge starts to increase. With increased discharge comes higher stage; eventually it is high enough to hydraulically lift

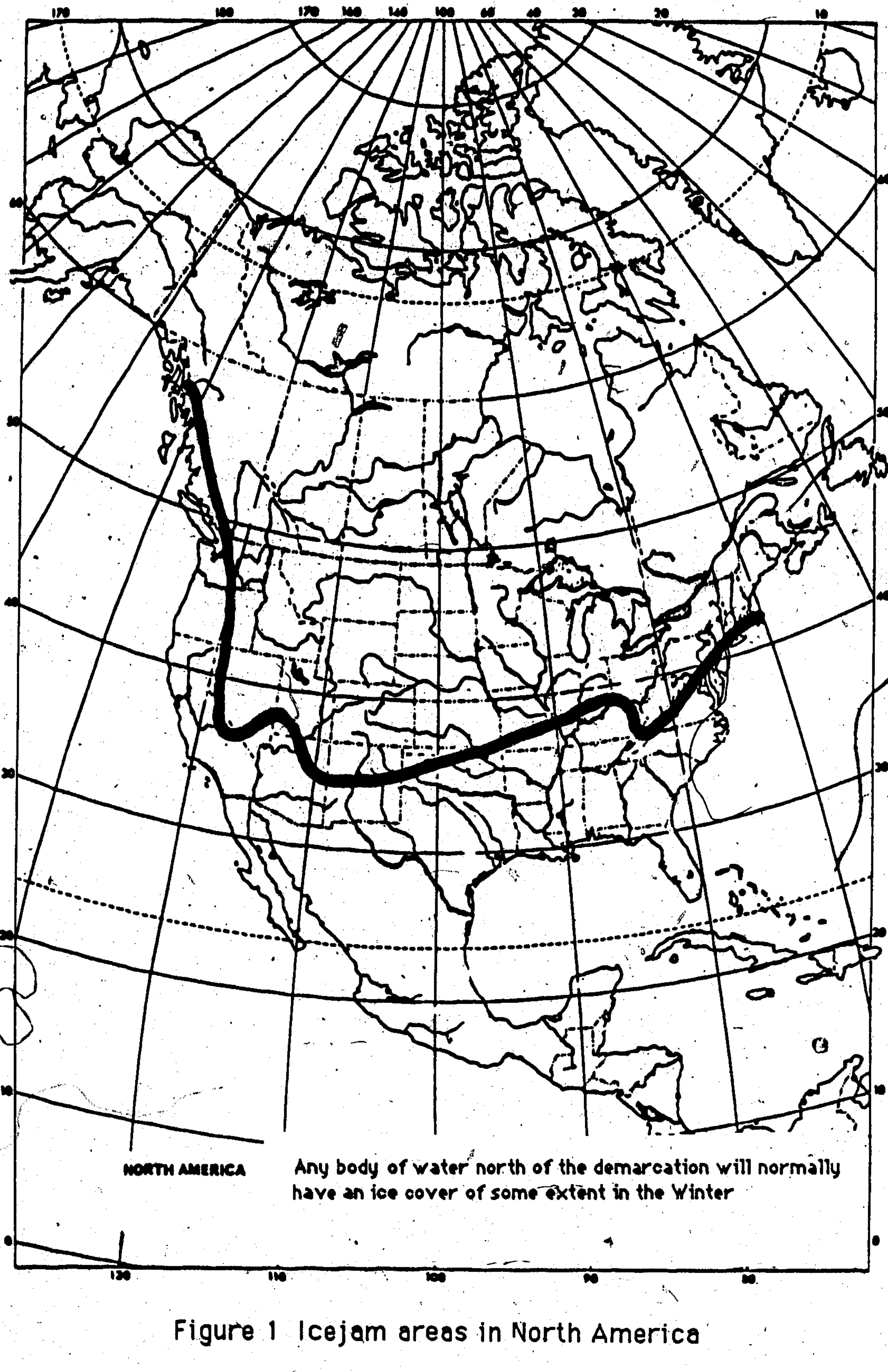


Figure 1 Icejam areas in North America

the river ice cover and detach it from the banks. Concurrently, the river ice weakens and decays due to exposure to direct solar radiation and the exchange of energy with the increasingly warm springtime atmosphere. At some time and place the force provided by flowing water is sufficient to break the ice cover into floes. These may encounter an impediment to their transit such as a section of river with an as yet intact ice cover, or a shallowed section of river in an area of greatly lessened bed-slope. At one or several of these places, the motion of the ice is retarded, and may stop, forming a jam. These can stall, or break and reform at any time, causing surges and other types of erratic flow at breakup. When a jam is strong enough, or well entrenched enough to remain in position, the stage begins to increase because of the resistance to flow under the jam. The increase in stage may become sufficient to cause the river to overtop its banks. Eventually the jam is destroyed by hydraulic forces, thermal decay or by a combination of both.

THE NATURE OF THE PROBLEM

Breakup is a complex phenomenon involving the interactions of meteorological and hydrological inputs, which produces what would appear to be a random output: the occurrence of an ice jam flood.

Breakup processes are governed, in part, by characteristics that are unique to a channel or catchment. These include abrupt changes in channel slope, latitudinal extent of the catchment, and climatic regime of the basin in question. Prowse (1986) indicates, for example, that the rapid reduction in the slope of the Liard River near Fort Simpson is one cause of ice jam formation at that point. Conversely, there are meteorological and hydrological factors that are common to all breakups or ice jams. In the determination of the relative importance of these common factors, one must consider not only the local geographic and climatic conditions, but also that an intrinsic variation from site to site is likely to alter the nature of the interaction between the common factors and local features, and thus change the specific characteristics of any derived relationships, if not their basic form. However, although there may be variations in the relationship of hydrometeorological variables to breakup at dissimilar sites, the underlying physical processes governing breakup should nevertheless be consistent, and any fundamental relations should be universal.

Any advance knowledge of the severity of break-up - the maximum stage attained by the river when in the midst of an ice jam flood - can be used to implement defensive strategies. However, as is true for all forecasting techniques, the longer the interval beween forecast and event, the less accurate and specific the forecast becomes. In this study, a method to predict the severity of breakup with some lead time or warning is the goal; a forecast of the actual timing of breakup itself is a secondary aim.

This study will generally rely on empirical techniques to determine relationships between hydrological and meteorological parameters and breakup on the Athabasca River at Fort McMurray, and to develop a forecasting method based on such relationships. Data used to derive the relationships will be used to provide a means of checking the performance of any forecast method created from the relationships, by "hindcasting".

Insight into physical processes may be provided by a separation of the processes into smaller and interrelated components. It is assumed that measurable meteorological variables do influence the nature of breakup, both individually through their unique characteristics and collectively, through their interrelationships. It is desirable that the unique function and the interactions of such variables, if any, be suggested by the nature of any relationships derived in this study.

PREVIOUS STUDIES

There have been several studies that have attempted to relate hydrometeorological antecedents to ice jamming at breakup. Shulyakovskii (1963) investigated the relation between the maximum stage caused by ice jamming at several sites to such variables as ice thickness, the depth of snow cover on the ice, the rate of change of stage prior to jam creation, an index comparing the energy input in the local ice jam area to the energy input in the region of flooding, and the occurrrence of negative air temperatures during the breakup period. He suggested, however, that not all of the above parameters would necessarily be involved in each breakup and so the prediction of maximum stage at all sites by the method did not depend on an input about every parameter. A sample calculation of the maximum stage at breakup for the Tom River at Tomsk was, for example, arrived at using an empirical equation of 4 parameters, based on 19 years of observations.

To predict the approximate time of breakup, Shulyakovskii examined the feasibility of using a "meriodonality index" - a parameter decribing the component of the upper atmosphere flow along the meridians at approximately 5400 m or the 500 mb constant pressure surface- over the Soviet Union. A large positive value indicates the presence of a ridge over the western half of the country and a trough over the eastern half, with corresponding southerly flow into, and warming of, the western region. If this pattern occurs in the spring, it results in an early breakup. Large negative values indicate northerly flow into, and thus lower temperatures at, the western region. This sort of pattern was said to delay breakup. Small absolute values indicated a predominately west-to-east flow, with little temperature changes in the region, and was thus an ambiguous and insufficient indicator of breakup timing. When applied directly to predicting the date of breakup, a method using a forecast of the upper atmosphere flow produced one month in advance of breakup was said to have some accuracy, but like the forecast, could be subject to large errors.

In Canada, Beltaos and Lane (1982) used stage increase above the maximum freeze-up stage as an indicator of breakup severity. They envisioned the breakup process to proceed as follows. When the surface energy balance becomes positive in the springtime, it is accumulated in flux density form (W /m^2 /day). A large sum prior to breakup indicates considerable thermal decay of river ice, hence a relatively low breakup stage. Conversely, a lesser accumulation of energy indicates the presence of strong ice, capable of contributing to a severe breakup. Meteorological parameters incorporated into an indicator of the energy balance of the ice surface, and presumed to determine the strength of ice included mean air temperature, hours of bright sunshine, wind speed and vapour pressure.To predict the time and stage of breakup, meteorological forecasts of the energy input parameters are used to determine future values of ice thickness for 3 to 4 days in advance of the date of forecast. Since the rise in stage is also a function of the sum of energy inputs, this too can be calculated using the same energy input equation. Finally, when the energy input causes a sufficient increase in stage to hydraulically displace the calculated thickness of ice, the stage of the river will exceed an empirically derived critical stage, and breakup will occur.

Beltaos and Lane concluded that stage was a useful indicator of breakup severity, but that the conclusions were site specific. Water Survey of Canada (WSC) estimates of discharge were used in plotting the effective daily stage prior to breakup. Mean daily discharge data were found to be inferior to estimates of the instantaneous discharge when plotting effective daily stage.

This investigation did not consider the method by which energy input translates into stage increases, as it did not discriminate between the increases in stage caused by increases in flow, caused by runoff, into the river catchment, and those stage changes resulting from the hydraulic, flow blocking properties of the ice in the flow.

White (1984) undertook a statistical analysis of 48 hydrometeorological factors and their relation to breakup on the Red Deer River at Red Deer, Alberta. Several multiple regression models of peak stage at breakup were derived. The best version considered several predominately locally important and somewhat arbitrtary parameters, including the occurrence and persistence of chinooks in the upper reaches of the basin, and achieved a correlation coefficient of 0.96. This highly empirical approach, however, greatly restricts the portability of its conclusions, though perhaps not the method. Moreover, little physical insight into river ice process is revealed by the function used to predict maximum stage, as the relationships between the parameters are not defined.

Gerard and Stanley (1986) investigated hydrometeorological aspects of ice jams on the Dawson River, Y.T. They speculate that both discharge and ice competence at breakup provided the best indicators of breakup severity. In this preliminary study, the exclusive use of meteorological parameters did not prove successful. Using trial and error, it was determined that the best index of discharge at breakup was a sum of the degree days of thaw accumulated 7 days before the event. Due to noise in the data, the relationship is somewhat indistinct, but a trend is evident. The discharge was compared to the sum of degree days of frost accumulated in the winter period prior to breakup, which itself was theorised to be an index of ice competence. A relationship between the above two parameters and stage at breakup with a considerable scatter about a best-fit discharge vs. accumulated degree days line was derived.

To measure the influence of ice strength at breakup on stage, the accumulated degree days of frost accumulated between freezeup and breakup was used as an index of ice thickness. The accumulated number of degree days of frost prior to breakup were superimposed on a plot already used to illustrate the relation between the sum of thawing degree days versus increase in stage prior to breakup. It was observed from the resulting pattern that when a plotted value of the two parameters on the axis of the chart crossed over a line of constant degree days of frost, breakup should occur on that day (Fig. 2). From this relationship it is theoretically possible to use forecast data to determine both the stage at breakup and its timing, the length of the forecast period being governed by the reliability of the meteorological forecast available.

Limitations of this method include its reliance on WSC discharge estimates, as a meteorologically based discharge estimate was not successfully derived. The influence of solar radiation on either ice competence and discharge was not included in this preliminary study.

Fogarasi (1985) studied the breakup of the Liard River in British Columbia from the perspective of the influences of synoptic meteorological patterns on the energetic inputs to the river and basin. Actually, the study was intended to be sub-synoptic, as it was claimed that "all weather factors that may influence a meso-scale ....breakup may occur over a spatial extent of 20 to 1000 km", but the lack of a dense climatic station network in the study area forced the reliance, in part, on synoptic-scale data. From a series of observations a climatic classification system was constructed, based on such parameters as wet-bulb potential temperature, the surface temperature anomaly, the 700 mb constant pressure surface height contour pattern (orientation), its persistence, and the meteorological phenomena associated with such a contour pattern over the study area, ie. warm or cold air transport, subsidence and ascent , radiation, and wind speed. Some classifications were ascertained to hasten breakup, others to impede it. Real time identification of a particular pattern, or the forecast of one, can be used to predict in a general sense if breakup is likely during the period of persistence of the pattern.

Fogarasi's study did not attempt to explicitly define or quantify those meteorological or hydrological agents responsible for breakup. Both the warm air transported into the basin and radiation were, however, suggested to be the parameters

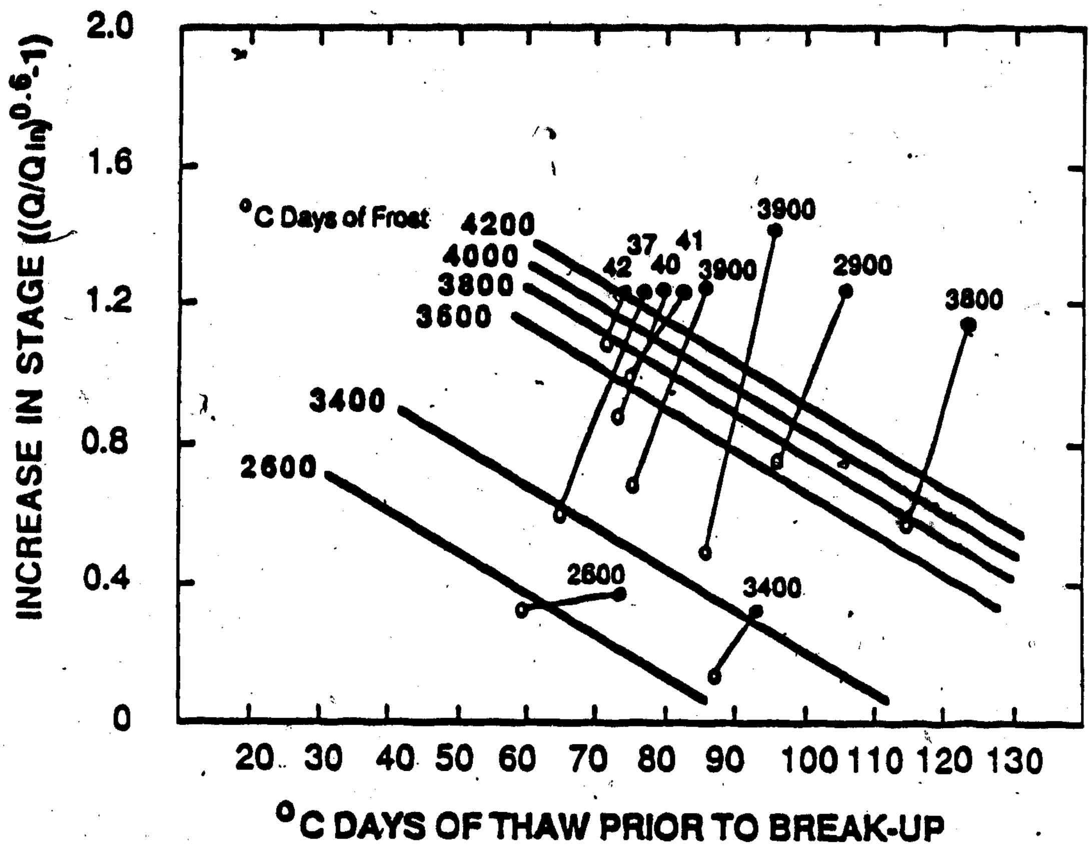


Figure 2 Adapted from Gerard and Stanley (1986). Relation between breakup and increase of stage, degree-days of thaw and degree days of frost; Yukon River at Dawson.

responsible for the breakup event. This method provides a means of determining both the air-mass, and the solar radiation properties from synoptic scale information, as meteorological activity at 700 mb is sufficiently elevated to be somewhat less directly affected by the small-scale features at the surface than is the activity measured at the surface by climate stations in the basin. Since local surface characteristics are not considered to be the primary control on breakup characteristics in this method, it seems to have a wider applicability than do techniques that depend on locally procured data.

McMullen (1961), in a rather qualitative manner, compared surface thermal characteristics and precipitation to the upper flow at 700 mb, and hence to stage and discharge at breakup on the Thames River in southwestern Ontario. It was concluded that 3 day forecasts of surface temperatures based on upper air data would have some utility in flood forecasting for the region.

Savchenkova (1972) used an index of the component of flow parallel to the meridians of the 500 mb flow to calculate the date of river breakup in the Soviet Union. If, in the month of March or early April, synoptic features are such that warm air transport prevails over the forecast area, a "spring synoptic season" circulation is established. When so established, the date of breakup can be predicted 15 - 20 days in advance and is predictable to the day, with an accuracy of 71% to 93%, about two weeks in advance.

Summary of Previous Studies

In the above investigations, either empirical surface studies or quasi-empirical upper air classification techniques have been used to describe the characteristics of river ice jam formation. Empirical surface studies have the benefit of some rigour, but are not directly portable. Upper air techniques have been generally too qualitative to be of direct use. A synthesis of the two techniques to produce a more comprehensive, and hopefully more realistic model of ice jam events and their relation to antecedent meteorology was the intent of this study.

Specifically, ice jam events on the Athabasca River at Fort McMurray and their antecedent meteorology were to be examined in detail to develop both an understanding of the breakup and ice jamming process, and a means of forecasting breakup conditions.

STUDY SITE DESCRIPTION

The Catchment

The Athabasca River rises in the Rocky Mountains south of Jasper. Its headwaters are located in the Columbia Icefields. About 130,000 km^2, or 80 percent, of the Athabasca River basin lies to the south and upstream of Fort McMurray. This section of the basin has a south-east to north-west orientation, and contains four major tributaries: the McLeod River, joining the Athabasca at Whitecourt; the Pembina River, flowing into the Athabasca at Flatbush; the Lesser Slave River, joining the Athabasca River at Smith; and, located just to the north of Fort McMurray, is the junction of the Athabasca with its largest tributary, the Clearwater River.

The main townsite lies within a small, flat, low lying plain surrounded by an area of slightly rolling countryside, positioned just south of the confluence of the Athabasca and Clearwater Rivers; as depicted in Figure 3. It is confined to the region beneath the 260 m surface contour. In addition, the town is bracketed by a small tributary of the Clearwater, the Hangingstone River, running south and east, and a small tributary of the Athabasca, the Horse River, to the south and west.

The River at the Townsite

At Fort McMurray the Athabasca changes from a confined channel of about 450 m width, with a slope of about 0.0010, to a wide channel with a gradient of about 0.00023 , and a 750 m channel width (Fig 4). Here, the peneplain adjacent to the river spreads horizontally, but the entrenchment of the Athabasca River valley remains about 100 m at the valley walls. In addition, the channel becomes imbued with islands and mid-channel bars (Kellerhals, Neill and Bray, 1972). The mean annual discharge of the river at the townsite is 675 m^3/s. The lowest discharge usually occurs in early March, and the maximum in early summer.

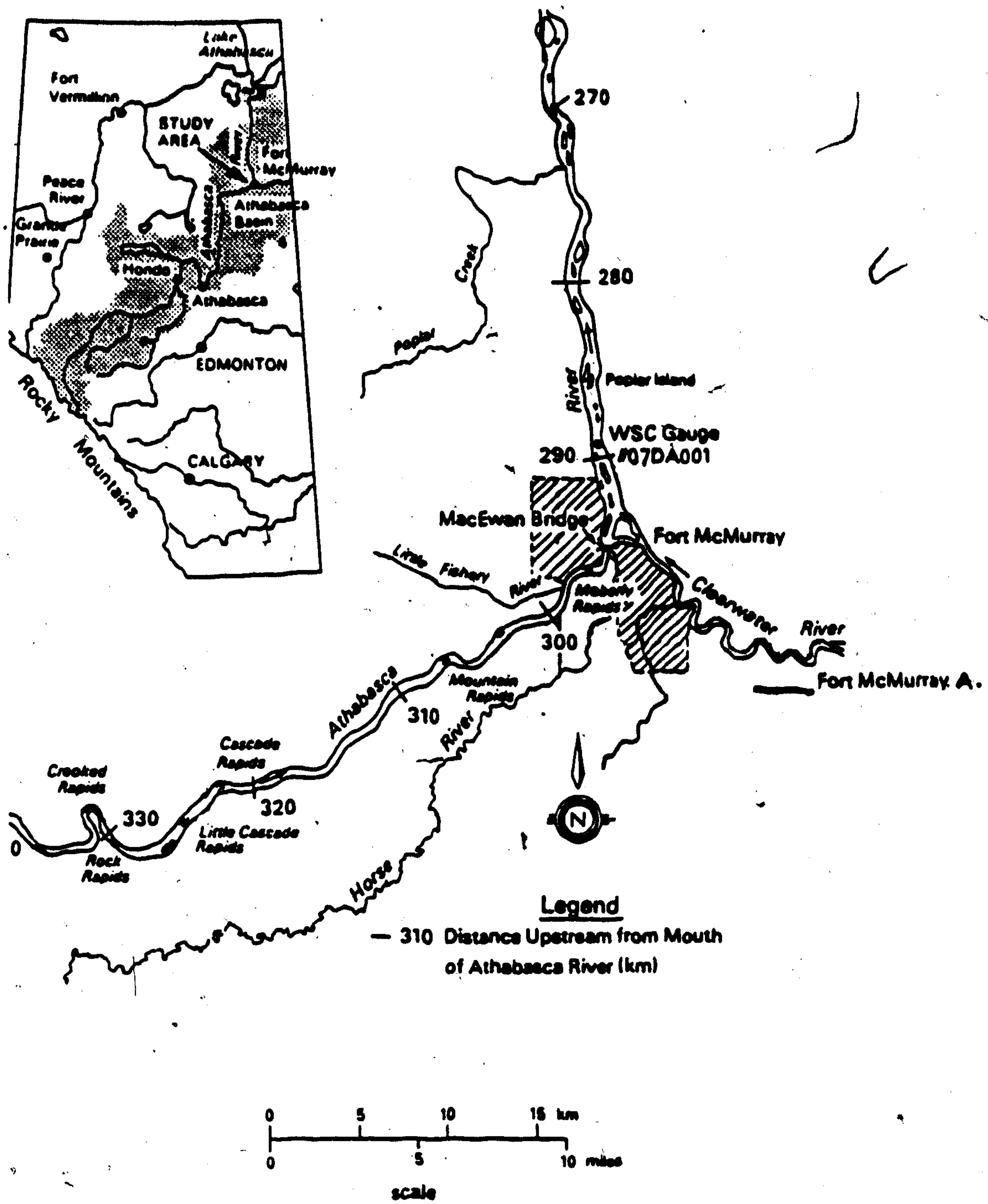


Figure 3 Basin and study areas (adapted from Andres, 1983)

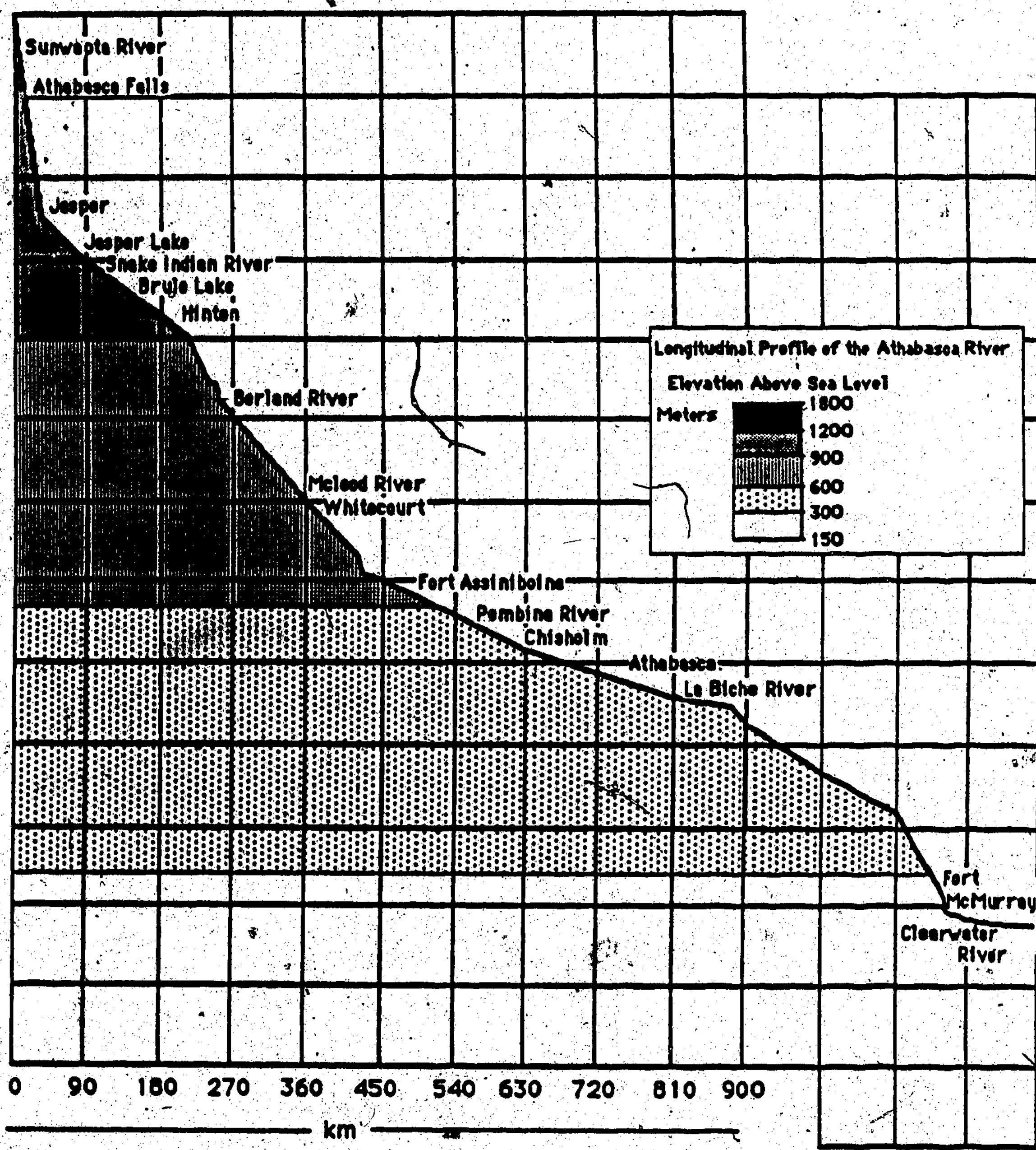


Figure 4 Athabasca River from Sunwapta River to Fort McMurray.
Adapted from Atlas of Alberta

Local Climate

Fort McMurray is located in a region of continental climate, characterised by long, cold winters, a rapid onset of spring, and short, warm summers. As expected of a region within an area of a continental control of climate, the mean annual daily maximum temperature is 5.3 °C, and the annual mean daily minimum is -6.8 °C. Longley (1972) provides a comprehensive view of the climatology of the Prairie Provinces. Climatic data of some Alberta sites and a detailed climatology of the Fort McMurray region are provided in Tables 1 and 2.

AVAILIABLE DATA

Meteorological and hydrological data are used in this study. The meteorological information was obtained from the records of synoptic information collected at Fort McMurray Airport. This class 'A' meteorological station commenced operation in 1953. It is located on a relatively flat section of the uplands just south of the Clearwater River valley, 13 km southeast of the Fort McMurray site. The data used includes daily records of precipitation, sunshine and temperature. It was obtained from the Atmospheric Environment Service (AES) in magnetic tape format.

Some hydrological data were abstracted from the Water Survey of Canada (WSC) "Surface Water Data" series of publications, in particular the information derived from the records of the Water Survey of Canada hydrometric station 07DA001 on the Athabasca River. This station has been in operation since 1958, and is located 3.5 km downstream of Fort McMurray.

Other sources of hydrological data for the Athabasca River at the townsite include WSC observer records, the actual stage hydrographs of the gauge downstream of Fort McMurray available at the Calgary WSC office, Blench (1964), and D. Andres (personal communication).

Table 1 Climatological data for selected municipalities in Alberta

Source: Longley (1972)

Station	Lat.	Long.	Mean annual temperature	Precipitation total	snow (cm)
Leithbridge	49°38'	112°48'	5.4	43.8	166.9
Calgary	51°06'	114°01'	3.6	44.3	148.6
Edmonton	53°43'	113°31'	2.7	47.3	136.7
Grande Prairie	55°11'	118°53'	1.4	43.9	166.4
Fort McMurray	56°39'	111°13'	-0.6	42.8	127.0
Fort Vermillion	58°23'	116°03'	-1.6	35.4	129.3

Table 2 Climate of Fort McMurray, including normals of temperature, precipitation, humidity, pressure, wind and sunshine.

Source: Atmosph[illegible]nvironment Service <u>Principal Station Data, Fort McMurray</u>

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp (C)												
Maximum	-16.5	-9.0	-2.2	8.7	16.9	21.0	23.1	21.4	14.8	8.6	-3.5	-12.2
Minimum	-27.1	-21.8	-16.1	-4.5	2.4	7.0	9.5	8.0	3.1	-2.0	-12.7	-21.7
Mean	-21.8	-15.4	-9.2	2.1	9.7	14.0	16.4	14.8	9.0	3.3	-8.2	-17.0
Precip-itation												
Rain (mm)	0.5	0.6	0.9	7.3	33.4	64.1	75.4	76.6	54.4	16.2	2.5	0.9
Snow (cm)	26.4	21.9	24.2	13.5	2.7	T	0.0	0.0	4.0	12.7	29.1	29.3
Humidity												
Vapour pressure (kPa)	0.13	0.19	0.26	0.45	0.68	1.03	1.27	1.21	0.86	0.56	0.31	0.18
Dew Point (C)	-22.9	-18.5	-13.2	-5.2	0.8	6.8	10.2	9.4	4.2	-1.8	-11.2	-19.1
RH. (%)	78	76	72	63	58	65	70	74	77	74	80	80
Wind												
Prevailing Direction	E	E	E	ESE	E	E	W	SW	W	E	E	E
Speed (km/h)	8.6	9.1	9.9	11.2	11.4	9.8	9.2	8.9	9.6	10.6	9.3	8.4
Sunshine												
Bright Sunshine (h)	88.2	129.3	165.1	231.6	276.4	272.6	285.4	24[illegible]	143.2	124.5	83.2	61.7
% of Possible	37.7	48.3	45.2	54.4	54.4	51.4	53.8	52.6	37.2	38.5	33.7	28.7

BREAKUP AND ICE JAM STUDIES AT FORT MCMURRAY

Typical jamming evolution

In general, breakup on the Athabasca in the vicinity of Fort McMurray begins upstream in the region of steeper gradient and rapids; after a period of some ice decay and increased flow in the channel. Upon arrival at the townsite, the speed of the flow will sharply decrease as a result of the diminished channel slope, causing a reduction in the momentum of the breakup front of ice, and a subsequent jamming against either the downstream intact cover of ice or a shallow region of the channel. Depending on the dimensions and longevity of the jam, a flood may result.

Previous studies

Until the WSC gauge was installed in 1958, accounts in historical records and the local media represented the entirety of available information on ice jam occurrence on the Athabasca at Fort McMurray. In 1964, a study was commissioned by the Provincial Planning Board of the Province of Alberta to investigate the characteristics of ice jams adjacent to the town site, with the objective of planning protective measures against the flooding caused by such jams (Blench, 1964). During this study, Blench compiled a historical chronology of ice jamming at the townsite from various sources, including Hudson Bay company records, local newspaper articles, and interviews with local residents.

Since 1974, a detailed investigation and documentation of ice jams at Fort McMurray has been undertaken by the Alberta Research Council and others under the auspices of the Alberta Cooperative Research Program for Surface Water Engineering. Physical effects of the jams such as extent of flooding, location, duration and damage have been recorded, along with an analysis of the hydrologic properties of the interaction of flowing water and ice with the river channel at the jam site, and a summary of some meteorological parameters, including precipitation, mean temperatures and degree days of thaw prior to jam (Gerard, 1975, Doyle, 1977, Doyle and Andres, 1978, 1979; Andres and Rickert, 1983, 1984, 1985).

It is clear from an analysis of the above sources that major ice jam floods on the river have occurred several times in the last century, the earliest being recorded in 1875 when the river rose 7 m above its banks. Other ice jam flooding has occurred in 1881, 1885, 1925, 1928, 1936, 1958, 1962, 1963, 1972, 1974, 1977, and 1979, with varying severity. Table 3 provides details of those events that have occurred at Fort McMurray since 1960.

STUDY OBJECTIVES

Because discharge and the competence of ice seem to be the main agents of breakup severity and since both presumably depend on antecedent meteorology, the overall objective was to define the relation between both maximum stage at breakup and the timing of breakup, and local antecedent meteorological conditions. The time of breakup is, for purposes of this study, said to occur when the maximum stage is reached at Fort McMurray following the commencement of either movement or melting of the ice cover, but before the water surface becomes ice-free.

The specific objective was to determine a set of relations that would allow several days of warning of breakup characteristics, based on current and forecast meteorological conditions at Fort McMurray. Additionally, it was hoped that such a set of relations would illuminate the meteorological components that have a significant influence on the formation of ice jams, and would thereby contribute to the understanding of the ice jam process.

In an effort to better determine the manner in which various factors influence breakup, an initial group of locally collected hydrologic and meteorologic factors were analysed, at first individually, then in concert. In accordance with the objective of providing a means of forecasting breakup parameters, it was decided to focus on a few of the more promising parameters, and thus simplify any derived relations. Finally, an attempt was made, in a preliminary fashion, to relate the significant local meteorologic factors to a more general synoptic perspective. This was intended to provide the basis for a long-term breakup forecasting technique, in a similar manner to those methods developed by Soviet and other researchers.

The initial requirement of the process is to investigate the hydrologic regime at breakup, namely, the discharge.

Table 3 Maximum stage and mean daily discharge on date of breakup for Athabasca River at Fort McMurray, 1960-1985

Stage Source Codes: 1. BLENCH-Blench Report, 1964
2. CHART-hydrograph chart record
3. DA - D. Andres, Alberta Research Council, personal communication

All discharge data from WSC Surface Water Data

YEAR	STAGE (m)	DISCHARGE (m^3/s)	SOURCE	NOTES
1961		796.0		
1962	242.66	976.9	BLENCH	corrected to WSC datum (235.66 m)
1963	244.06	1359.0	BLENCH	recorder malfunction
1964		283.0	CHART	recorder malfunction April 15
1965		643.0	CHART	
1966	239.6	507.0	CHART	
1967	>238.8	595.0	CHART	discontinuous record at breakup
1968	238.4	377.0	CHART	breakup not distinct-thermal breakup
1969	239.0	646.0	CHART	discontinuous record at breakup
1970	238.4	178.0	CHART	
1971	239.0	513.0	CHART	
1972	244.69	779.0	CHART	
1973	240.36	286.0	CHART	
1974	243.76	1133.0	CHART	
1975	>238.7	765.0	CHART	discontinuous record Apr. 26
1976	242.36	991.0	DA	
1977	244.16	775.9	DA	
1978	238.66	544.5	DA	
1979	242.66	1366.0	DA	
1980	240.66	574.7	DA	
1981	240.66	558.3	DA	
1982	238.86	560.0	DA	
1983	237.66	596.0	DA	
1984	240.16	650.0	DA	
1985	241.16		DA	

CHAPTER 2

DISCHARGE ANALYSIS

Background Information

An analysis of available (WSC) data indicates that, although available hydrologic data are usually accurate and reliable, it is necessary to synthesize data for a short pre-breakup period, because the recorded observations from this period are often unreliable. It is assumed that the meteorological data for the site are generally reliable for the study period.

In comparison, hydrological data are generally only reliable only during periods of relatively quiescent flow, up to a few days before breakup. Furthermore, at the initiation of breakup, ice will damage the orifice of the WSC gauge, rendering it inoperable, and hence the flow information unavailable, as seen in Figure 5. Similarly, observer estimates of discharge do not seem to be reliable during ice jamming or other periods of disturbed flow (Doyle and Andres, 1979). Even when stage data during breakup are provided by a functional gauge, one must consider what the effect of ice and its hydraulic roughness will have on estimates of discharge. Several studies have tried to relate discharge to roughness, hydraulic radius, channel slope and the flow area underneath the ice cover during breakup, but with dubious accuracy, as the flow must be assumed to be steady, and one must estimate roughness parameters from data describing the pre-breakup ice characteristics (Andres and Rickert, 1985)

As a consequence of the difficulties of obtaining accurate discharge information at breakup, it was felt that a discharge model based solely on antecedent meteorological conditions could potentially be more useful.

A sufficient discharge to cause breakup requires a large enough input of energy or rainfall into the snowcover of the basin to cause sufficient meltwater to be produced. Of course, a significant fall of rain on to a snowcover may rapidly produce a tremendous volume of runoff in a basin (Thompson and Sporns, 1962), but at Fort McMurray, too little precipitation falls in the form of rain during the breakup period to greatly influence the net input of energy and hence the rate of runoff. Figure 6 compares

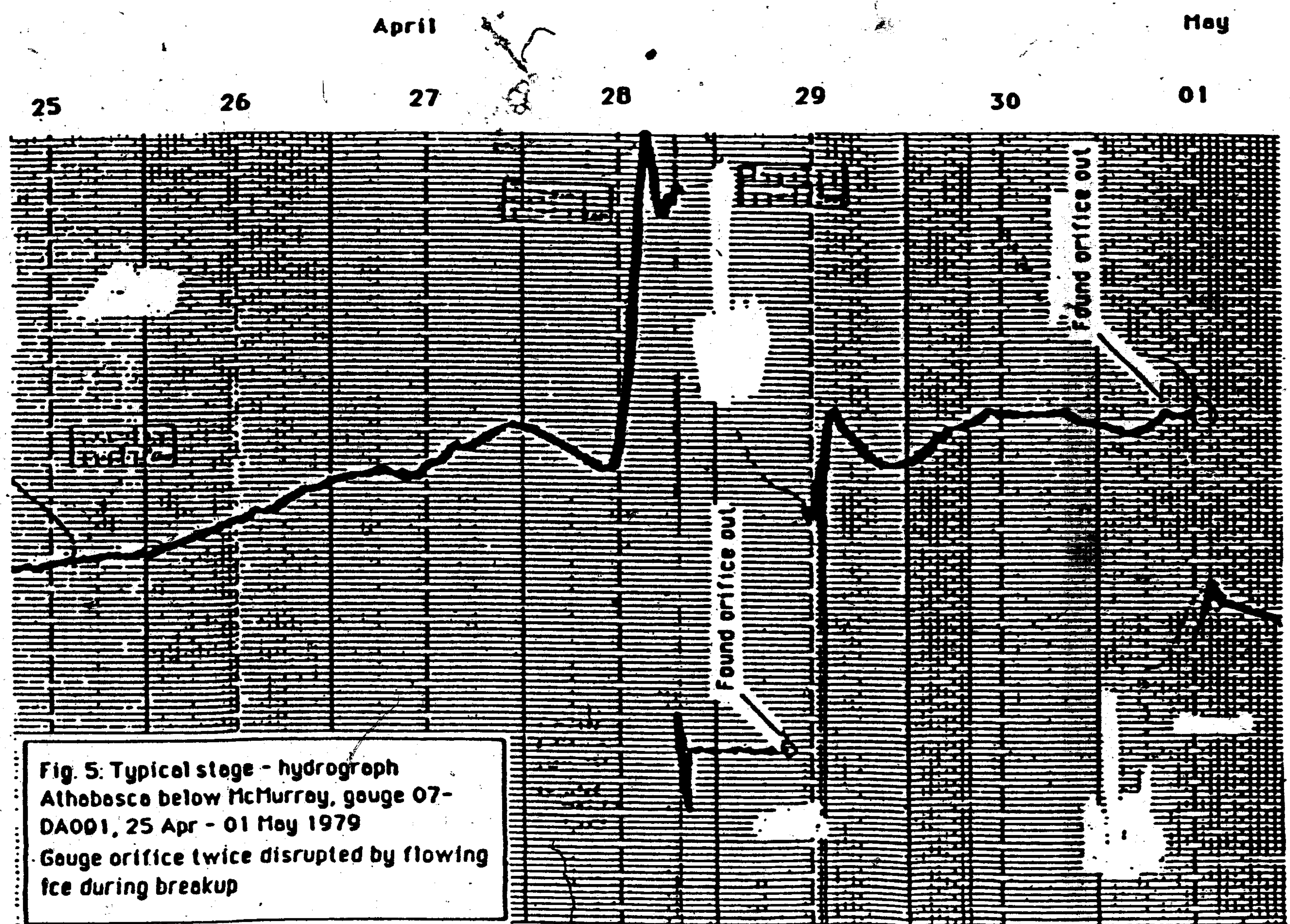


Fig. 5: Typical stage - hydrograph Athabasca below McMurray, gauge 07-DA001, 25 Apr - 01 May 1979
Gauge orifice twice disrupted by flowing ice during breakup

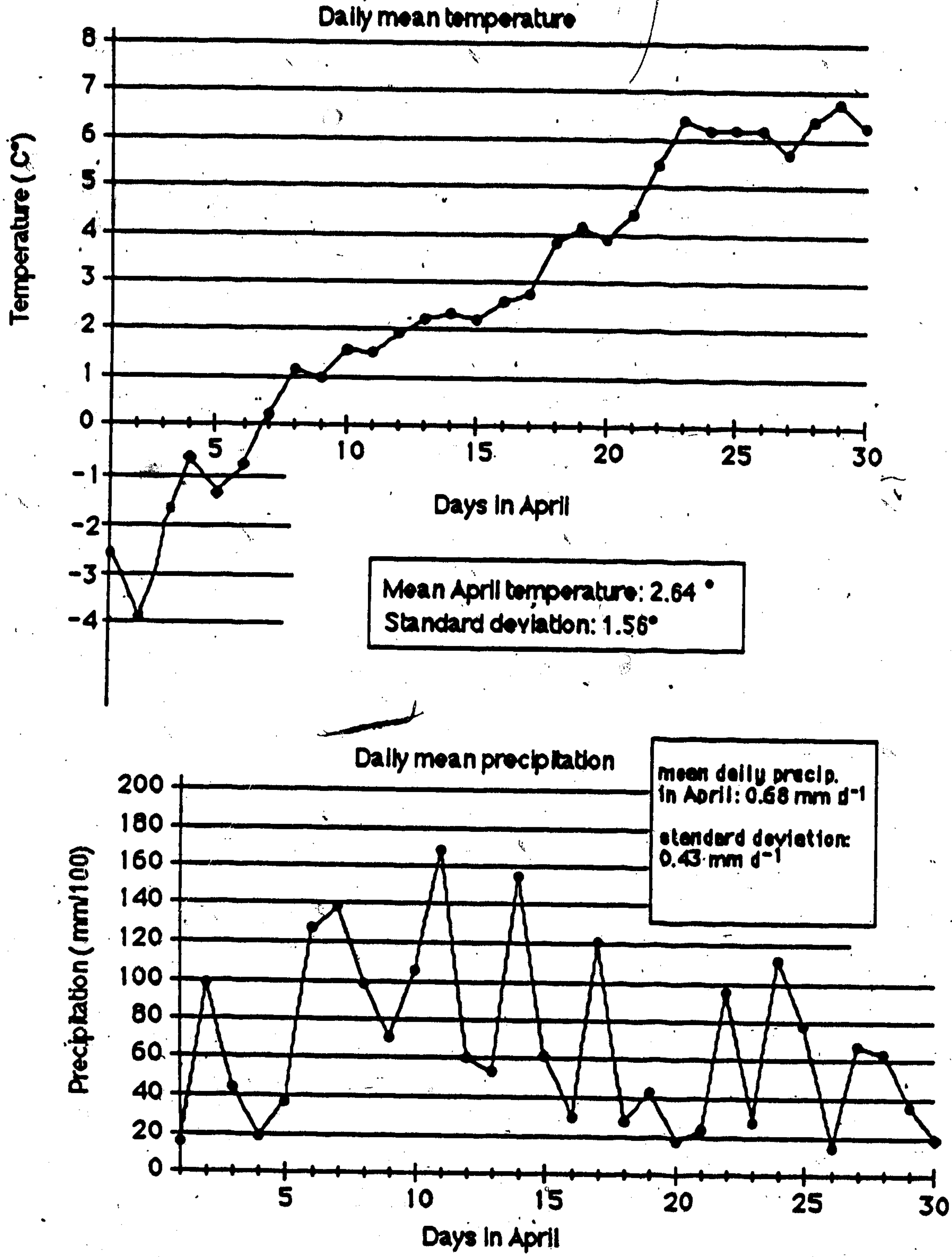


Figure 6 Temperature and precipitation trends on a daily basis, for 24 years of record, 1960 - 1984

mean daily temperature to precipitation for April at Fort McMurray, over a 25 year period (1960-1984). It can be seen that little precipitation falls during this month, and temperatures remain near zero for the first half of the month. Even when falling as rain, it is unlikely that April precipitation will often contribute significantly to the spring runoff. Upstream in the basin, precipitation patterns are similar. Hence, in this analysis, it was assumed that snowmelt was the sole source of discharge increase.

Significant sources of incoming energy at the study area can be crudely parameterised by meteorological indices; two of the most readily available are degree days of thaw and solar radiation. Theoretically, both degree days of thaw and bright sunshine should be related to discharge, as energy input from both the transfer of sensible heat from the air to the snowcover and direct radiation from the sun will cause melting of the pack if the temperature of the snow can be raised to the melting point (Oke,1978). Storr (1978), in an examination of snowmelt at Marmot Creek, Alberta, used the U.S. Corps of Engineers theoretical model of daily snowmelt. It was determined that during the so-called melting season in a region of partial forestation similar to the Fort McMurray area, shortwave (direct solar) radiation was responsible for 78% of calculated melt, with long wave energy accounting for nearly all of the remainder. The component of melt resulting from long wave energy was described by a linear function containing parameters such as the difference in the environmental temperature, measured at 3 m above the surface, and the surface (snowpack) temperature. Appendix A contains the U.S. Corps of Engineers snowmelt model.

The measured daily solar radiation shows a good linear correlation with the daily duration of bright sunshine throughout Alberta. Typical relationships are given in Table 4 and Fig. 7. Similar relationships have been established by many researchers, for example Goodison (1972). As a consequence, it was decided to use hours of bright sunshine as an index of incoming solar radiation. To measure bright sunshine, AES uses a Campbell-Stokes sunshine recorder. Appendix B describes the use of the device.

For reasons of simplicity, it was decided to use degree-days of thaw (mean daily temperature above 0° C) as an index of sensible heat. Other researchers, including Prowse (1986), Gerard and Stanley (1986), and Beltaos (1984) have used degree days in the same manner. According to Quick (1986), degree days of thaw is also a useful

Table 4 Relation between hours of bright sunshine and radiant flux (Global Solar) received at the surface on a daily basis for various sites and years in Alberta, during April.

R= net global solar surface flux in Wm^{-2} and S= units of 1/10 h. of bright sunshine received each day-no correction for solar angle: see Titus, R.L. and Truhlar, E.J., A New Estimate of Global Solar Radiation in Canada, DoT, Meteorological Branch, CLI 7-69.

r^2 = square of correlation coefficient

year	Radiometer /Sun recorder site	Function	r^2
1964	Edmonton Industrial Airport	$R=1.125*10^7+1.178*10^5$ S	0.835
1964	Suffield Airport	$R=9.196*10^6+1.250*10^5$ S	0.905
1969	Stoney Plain/Ed. Ind. A	$R=9.388*10^6+8.576*10^4$ S	0.718
1969	Suffield Airport	$R=7.832*10^6+1.281*10^5$ S	0.911
1972	Stoney Plain/Ed Ind. A	$R=8.434*10^6+1.078*10^5$ S	0.847
1972	Suffield Airport	$R=9.807*10^6+1.023*10^5$ S	0.853
1972	Beaverlodge A.	$R=9.555*10^6+1.105*10^5$ S	0.896
1974	Stoney Plain/Ed. Ind. A.	$R=9.049*10^6+1.201*10^5$ S	0.883
1974	Suffield A,	$R=8.208*10^6+1.302*10^5$ S	0.937
1974	Beaverlodge A.	$R=9.545*10^6+1.003*10^5$ S	0.875
1975	Stoney Plain/Ed. Ind. A	$R=1.221*10^7+9.707*10^4$ S	0.642
1975	Suffield A.	$R=1.195*10^7+1.188*10^5$ S	0.783
1975	Beaverlodge A.	$R=1.126*10^7+9.156*10^5$ S	0.773
MEAN VALUE		$R=9.826*10^6+1.104*10^5$ S	

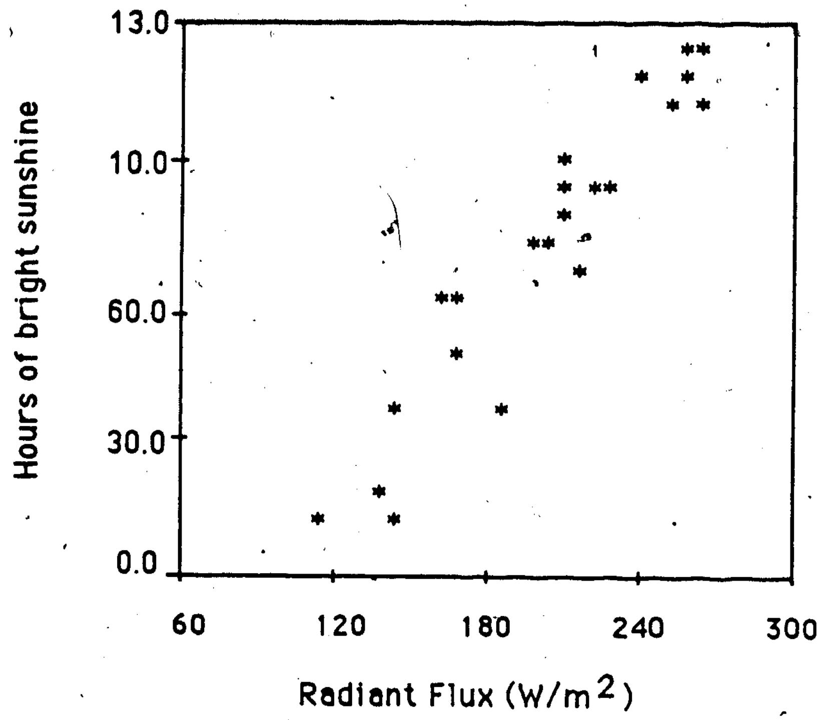


Figure 7 A typical bright sunshine versus solar radiation relationship, in Alberta, in April. (Edmonton Industrial Airport, April 1966)

index of net longwave radiation.

As both bright sunshine and degree days of thaw were clearly implicated in snowmelt, it was decided to investigate their connection to discharge during the pre-breakup period. Some meteorological data are not availlable for the early part of the study, however. Sunshine data, for example, were not available prior to1972. Hence most of the anaylsis is performed using meteorological data from 1972-1984.

Data Appraisal

If the snowpack in the basin is too cool, radiation will not create runoff. The accumulation of hours of bright sunshine is therefore subject to the condition that the mean daily temperature remain above about -5 °C, as it is assumed for purposes of this analysis that any melt produced at a lower ambient temperature would likely not remain in the liquid state, but would refreeze within the pack (it has been established that snowmelt can occur in negative air temperatures in the presence of sufficient solar radiation, although given a sufficiently low air temperature the quantity of melt will be negligible (Oke, 1978)).

To detect if any potential spurious correlation exists between accumulated daily bright sunshine and daily degree days of thaw, a regression was performed between the two as recorded at Fort McMurray. Figure 8 illustrates the relationship found between hours of bright sunshine and degree days over a seven day period, an interval judged sufficiently long to establish their relationship. Evidently, the two variables are not closely related. This is to be expected, as degree days of thaw is an average diurnal temperature, and so considers 24 hour temperature values, whereas bright sunshine should have an influence primarily on daytime temperatures. The two parameters were therefore considered to be independent for the purposes of this study.

To appraise the supposition that degree days of thaw and hours of bright sunshine can be used to quantify the discharge of the Athabasca River at Fort McMurray, the sum of degree days of thaw and hours of bright sunshine on a daily basis at Fort McMurray were compared to the increase of discharge that occurred during both the entirety, and various sections of, a period of more-or-less steadily increasing

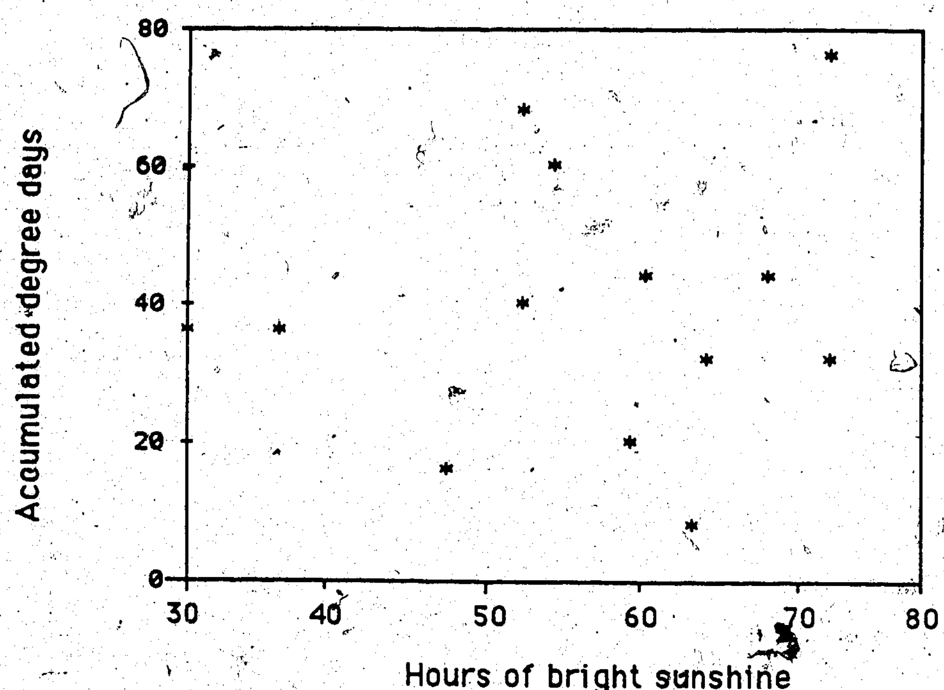


Figure 8 The relationship between accumulated hours of bright sunshine, and accumulated degree days of thaw, over one week prior to breakup at Fort McMurray

discharge of the Athabasca River at Fort McMurray (Table 5). A smooth increase of discharge over the period of comparison was an additional prerequisite of the model, since the absence of an increase would not reveal any information about basin melt -except that if it were occurring, the water was not reaching the main flow. Furthermore, in the period close to breakup, rapid fluctuations in discharge over short periods are caused by hydraulic events, (such as a jam collapse upstream) which obscure the hydrometeorological relationships.

Ideally, the period of the comparison of bright sunshine and degree days to the increase of discharge should be as close to breakup as possible. Hence, the final days prior to the end of steadily increasing flow were chosen for the analysis. The period should also be sufficiently short, if possible, as to permit the use of meteorological forecasts to estimate future discharge.

Regression Analysis

Using trial and error, it was determined that the accumulation of degree days of thaw, and hours of bright sunshine in a four-day period immediately prior to the cessation of steadily increasing flow (labeled T_{4Q}) correlated well with the change in discharge over the same time. Figure 9 illustrates the relationship between accumulated degree days of thaw and discharge and Figure10 reveals a corresponding relationship for accumulated hours of bright sunshine, both over T_{4Q}. Table 6 provides the data used to derive the relationships.

When accumulated hours of bright sunshine and degree days over the four day period were together compared to the net increase in discharge by means of multiple regression, the following relationship was found:

$$(1) \qquad \Delta Q = 2.51\Sigma\,(\text{degree days}) + 4.0\Sigma\,(\text{hours of bright sunshine})$$

was found, where ΔQ is the change of discharge in m^3/s. The correlation coefficient of the relation is 0.97. Figure 11 illustrates the comparison of the calculated discharge increase to that measured over twelve years. This relation is far superior to that possible

Table 5 Meteorological and Hydrological data, Fort McMurray

Year	Begining of discharge increase	End of increase	Duration (days)	Increase of discharge (m^3/s)	Accumulation of bright sunshine (h)	Accumulation of degree days (°C days)
1960	Mar 20	Apr 15	26	98		
1961	Mar 15	Apr 28	44	344		44.0
1962	Apr 1	Apr 17	17	216		35.1
1964	Apr 5	Apr 21	17	106		38.1
1965	Apr 7	Apr14	8	227		25.2
1966	Apr 1	Apr 15	15	161		21.0
1967	Apr 10	Apr 28	18	434		29.2
1968	Apr 9	Apr 27	19	128		56.5
1969	Apr 6	Apr 14	9	359		54.3
1970	Mar 16	Apr 7	22	36		
1971	Apr 5	Apr 20	16	351		71.7
1972	Apr 7	Apr 22	16	485	91.6	17.2
1973	Apr 8	Apr 18	11	100	108.3	44.9
1974	Apr 9	Apr 19	11	754	100.8	62.5
1975	Apr 17	Apr 25	9	396	82.2	53.2
1976	Apr 2	Apr 12	11	643	109.3	91.5
1977	Apr 2	Apr 15	14	577	102.1	69.4
1979	Apr 13	Apr 28	16	639	92.5	27.2
1980	Apr 2	Apr 14	13	238	[illegible]04	68.2
1981	Mar 25	Apr 10	17	390	151.5	0.0
1982	Apr 10	Apr 25	16	360	124.8	54.0
1983	Apr 03	Apr 18	16	210	106.1	65.8
1984	Mar 20	Apr 10	22	300	138.6	92.8

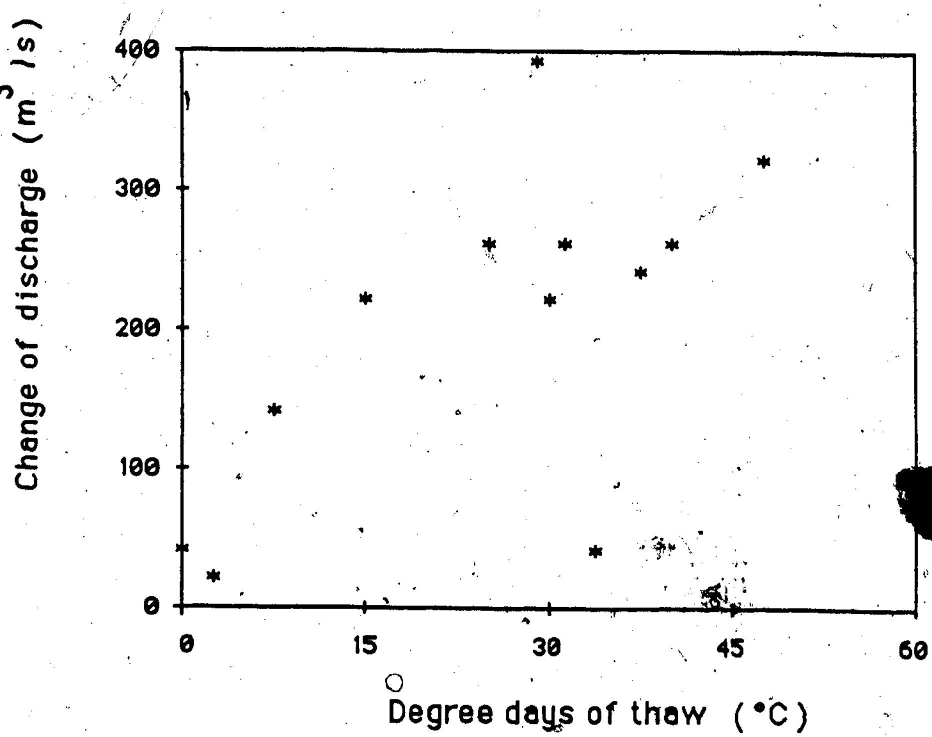


Figure 9 Comparison of the change of discharge to accumulated degree days of thaw, during T_{4Q}

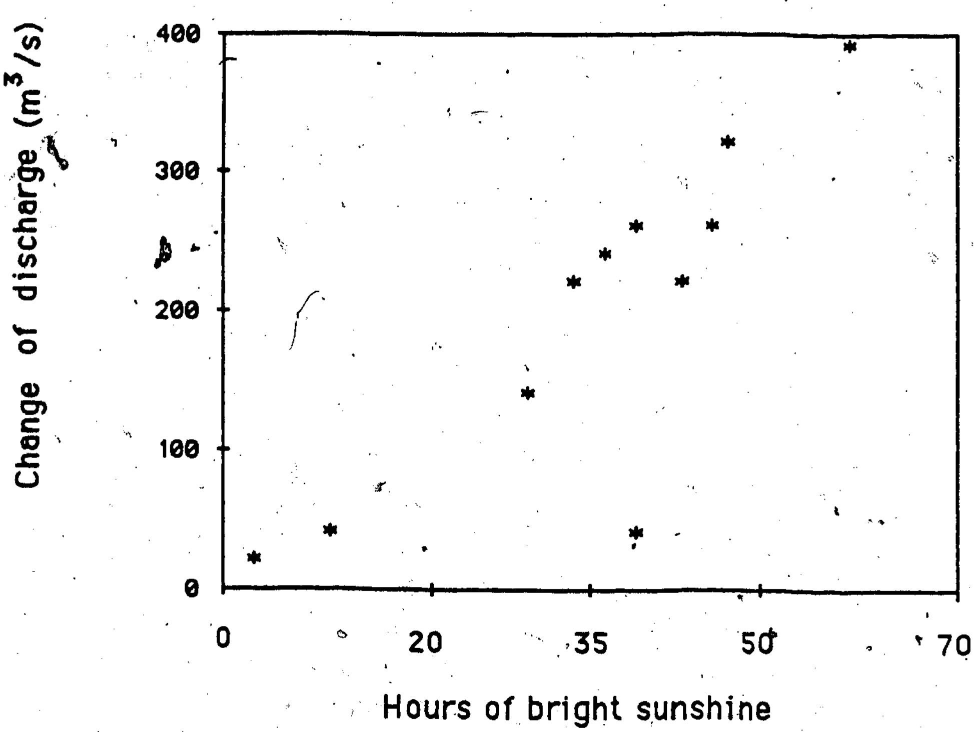


Figure 10 Comparison of the hours of bright sunshine accumulated during T_{4Q}, to the change of discharge over the same period.

Table 6 Comparison of bright sunshine and degree days of thaw to discharge

Nomenclature: Qs is the mean daily discharge on the last day of steadily increasing discharge measured in m^3 / s. Qs - 4 is the mean daily discharge in m^3 / s, measured 4 days prior to the end of steadily increasing discharge. ∂Qs is (Qs) - (Qs-4). The degree days accumulated during the 4 days is Σdd, and the hours of bright sunshine accumulated over the same period is labeled ΣR.

Year	Days	Q	Qs - 4	∂Qs	Σdd	ΣR
1983	Apr 15 - 18	469	289	180	30.0	33.7
1982	Apr 22 - 25	460	200	260	30.7	46.9
1981	Apr 07 - 10	620	444	169	7.3	29.8
1980	Apr 11 - 14	453	308	145	37.1	36.0
1979	Apr 24 - 27	578	395	183	15.3	43.8
1978	Apr 11 - 14	484	445	39	2.5	3.2
1977	Apr 12 - 15	855	591	264	40.2	39.7
1976	Apr 09 - 12	878	509	369	47.7	48.3
1975	Apr 22 -25	651	353	248	34.0	39.3
1974	Apr 15 - 18	681	278	403	30.0	59.4
1973	Apr 17 - 20	386	250	137	25.1	47.2
1972	Apr 07 - 10	311	270	41	0.0	9.9

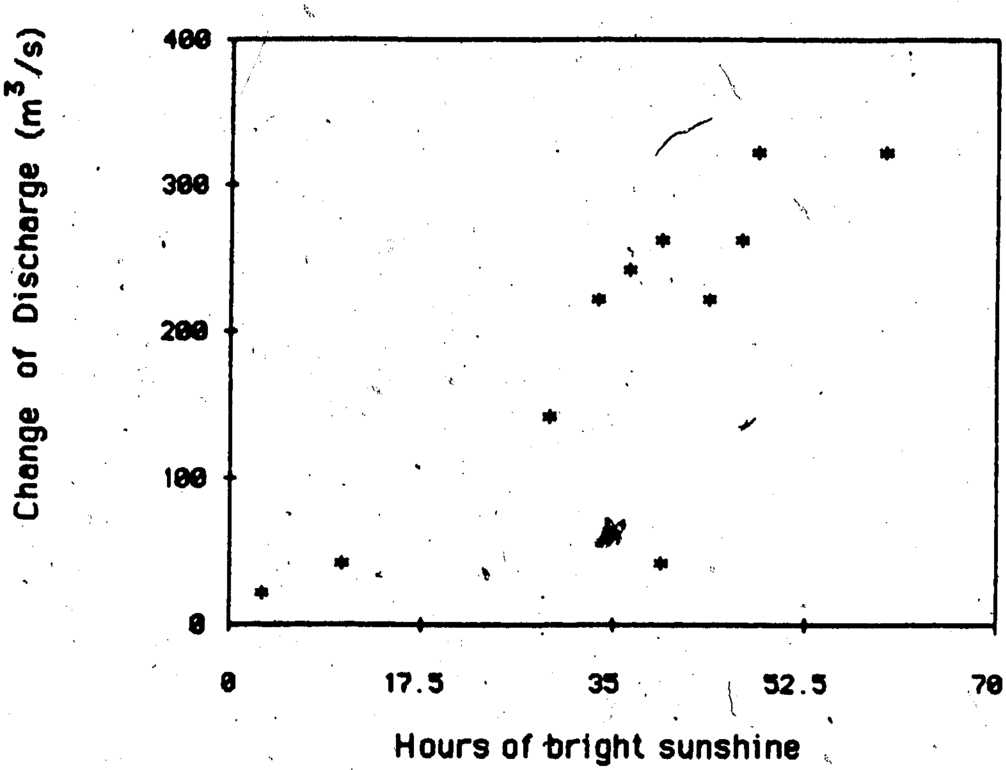


Figure 10 Comparison of the hours of bright sunshine accumulated in the four days prior to the cessation of steadily increasing flow, to the change of discharge over the same period.

when using degree days or hours of bright sunshine separately as a measure of discharge.

Discussion of the discharge equation

The comparison of measured to calculated discharges indicates that Equation 1 can be used to provide reasonable forecasts of discharge increase over the breakup period when reliable hydrological data is unavailable.

Both the parameters used in the model and the time scale seem to successfully predict most of the change of discharge as seen in Figure 11. There is one year in the data, however, that does not fit the regression as well as the rest: In 1984 the predicted discharge was a significant underestimate. A further examination of the meteorological record indicated that over 10 mm of precipitation in the form of rain fell in the week prior to the cessation of smoothly increasing flow. Even though the climatological record indicates that rainfall at this time is unusual, the effect of rain on pre-breakup discharge must be considered if estimates are to be accurate.

To determine if a lag existed between the snowpack melt as described by the meteorological parameters, and the subsequent increase in discharge, the measurement of discharge change was initiated after one, two and three days accumulation of the meteorological components had commenced. There was no improvement in the relation.

Fortunately, for forecasting purposes, the best correlation between meteorological variables and the increase in discharge occurred over a four day period, as this length represents the limit of reasonable accuracy of meteorological forecasts, and hence the limit of any discharge forecast based on meteorological data.

Figure 12 illustrates the various portions of discharge increase resulting from the runoff created by degree days and bright sunshine for 12 years of record, as determined by Equation 1. In general, the solar radiation makes the larger contribution. This is consistent with the conclusions drawn by the U.S. Corps of Engineers study.

It can be argued that substantial portions of the basin are the sources of runoff. However, since 4 days seems to be the period required for snowmelt to produce the discharge required to force breakup, any concurrent discharge increase must result

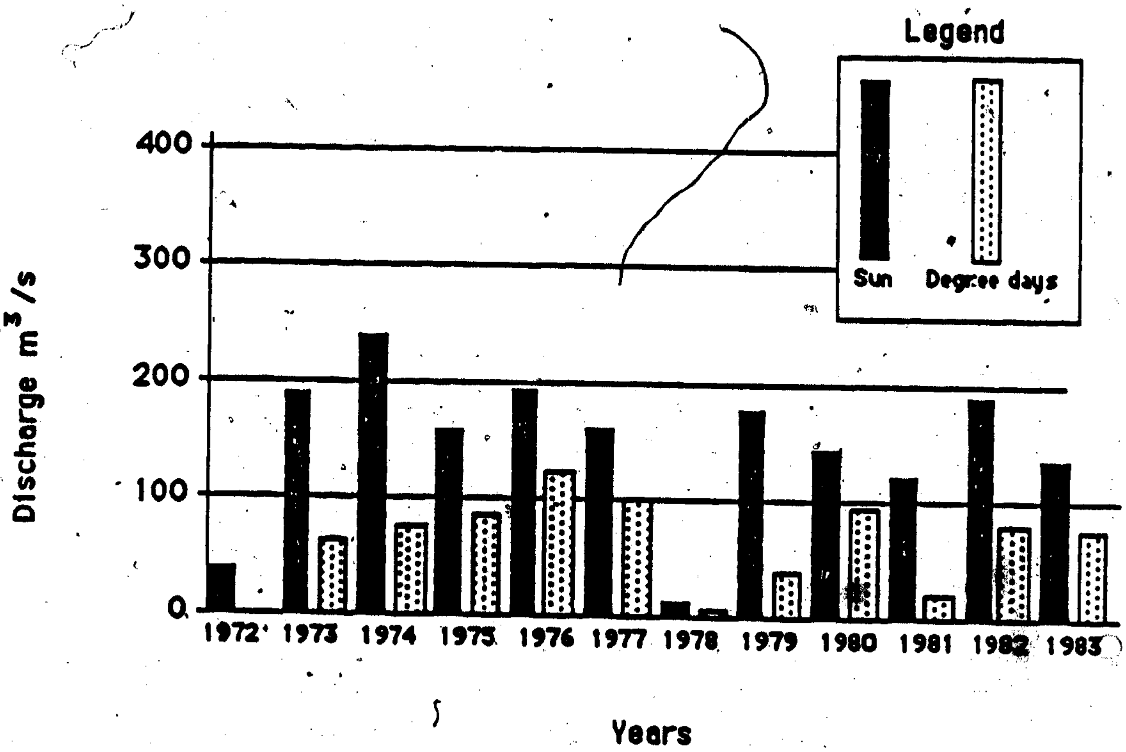


Figure 12 The comparison of hours of bright sunshine and degree days of thaw as producers of snowmelt.

from the snowmelt in a region defined by the speed of the meltwater through the basin and into the stream during that period. If 1 m/s is used as a very rough estimate of the celerity of the runoff, then the most distant significant source of meltwater is about 350 km from the townsite.

This figure, although only an order of magnitude estimate, suggests that the use of meteorological data gathered solely at Fort McMurray airport is reasonable. There are, of course, spatial variations of climate in the Athabasca River basin, but the magnitude of variation encountered over the 350 km upstream of Fort McMurray, as distant as the town of Smith, is not large. The closest meteorological station to Smith is at the Town of Athabasca, 35 km to the southeast. Figure 13 provides a comparison of the daily mean temperature at Fort McMurray and Athabasca, in April, 1982. It is apparent that the daily means at both sites are well correlated. Andres and Rickert (1985) also determined that the mean temperature trends for Fort McMurray, Slave Lake, Whitecourt and a field site, 100 km south-west of Athabasca in April, 1984 were very similar.

Sunshine, as measured at the site nearest to Smith with a sunshine recorder, namely Slave Lake Airport, seems to be more spatially variant than is temperature. Figure 14 illustrates the correlation of daily values of bright sunshine accumulated at Slave Lake Airport versus that at Fort McMurray airport for April, 1982. It is evident the two are essentially independent. The Slave Lake Airport is, however in a region where orographic cloudiness is not unusual. Ten km to the south-west are the Swan Hills, and to the north-east at the same distance are the Pelican Mountain Uplands. During periods of either easterly or westerly flow the Slave Lake region is likely to be more cloudy than is Fort McMurray, assuming an air-mass of more-or-less uniform characteristics prevails over both locales.

The physiography of the region surrounding the Town of Athabasca is, however, similar to that of Fort McMurray, and so not as prone to orographic effects. In the absence of better data, it was asssumed that the sunshine characteristics of the Fort McMurray region were representative of an area large enough to account for the sources of meltwater influencing the volume of discharge. The validity of this is borne out by the success of the discharge regression.

Equation 1 provides the means for estimating the expected increase of discharge, with 4 days warning, and hence a method to predict the net discharge on the

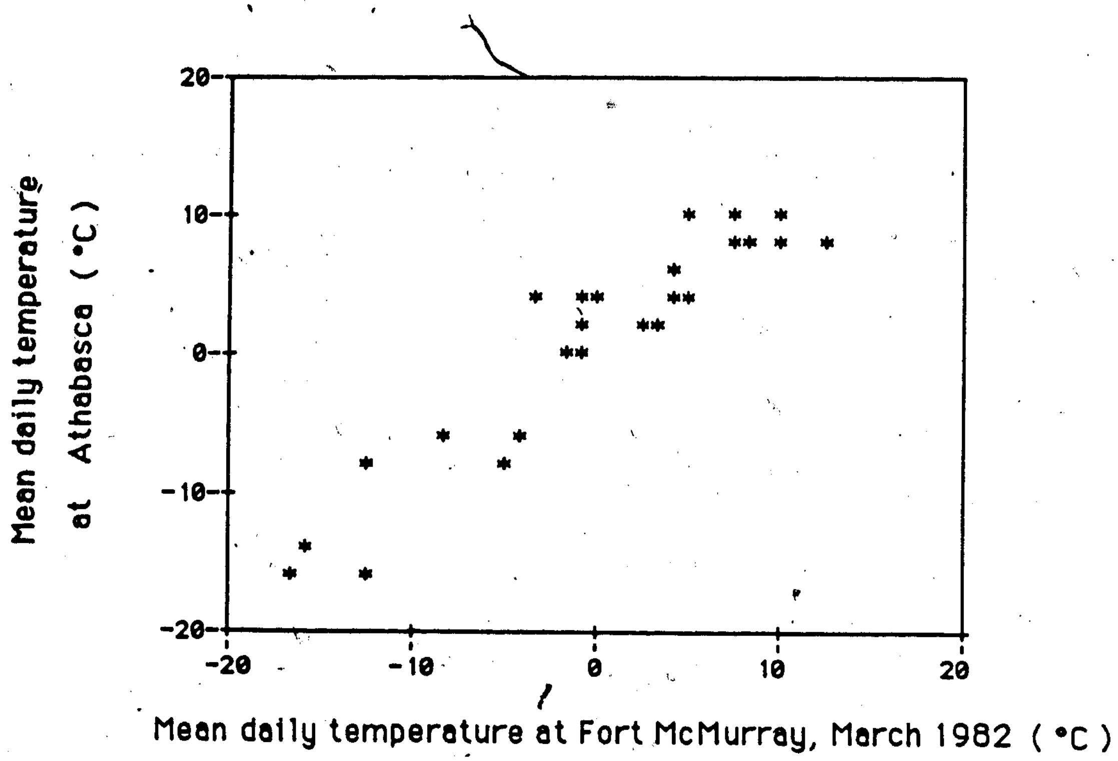


Figure 13 Comparison of the mean daily temperatures of Fort McMurray and Athabasca, March 1982.

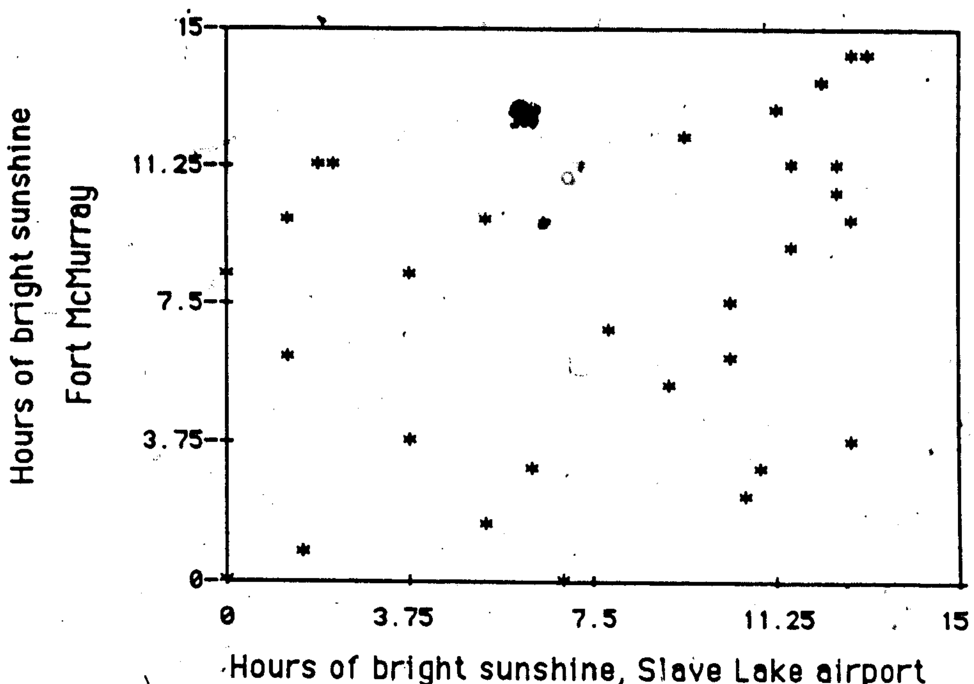


Figure 14 Hours of bright sunshine for Fort McMurray and Slave Lake, on a daily basis, April 1982

date of breakup. This estimate will be independent of flow irregularities caused by caused by upstream hydrologic events.

Discharge forecast method

Based on the above analysis, the following forecast method is proposed: when it becomes apparent from daily discharge estimates that a steady increase in discharge is beginning in the springtime, the discharge can be estimated using Equation 1 for three days hence from the current days data, and three-day forecast temperatures and estimates of cloudiness. The forecast temperatures will permit a direct estimate of degree day accumulation over the subsequent three days. For bright sunshine, a forecast of "sunny", for example, can be interpreted as an indication that the entire daylight period should be included in the accumulation of hours of bright sunshine. Table 7 provides an interpretation of the component of a general weather forecast regarding the expected duration of sunshine. The use of a general forecast does not preclude the use of specialised information obtained from a meteorologist at a weather centre.

It now remains to relate the discharge at breakup and other parameters to the maximum stage that is likely to occur at breakup - the chosen measure of the severity of breakup.

Table 7 Atmospheric Environment Service Definitions of Sky Conditions

Forecast	Meaning
A) CLEAR	For use when the amount of cloud is expected to be less than 2 tenths, thus implying a virtually "cloud free" condition
B) SUNNY FEW CLOUDS	For use when the cloud amount is expected to be 2 to 4 tenths or less
C) MOSTLY (MAINLY) CLEAR OR SUNNY	For use when the cloud amount is expected to be less than 5 tenths. However, there may be periods of as much as 5 hours when there is expected to be greater amounts of cloud.
D) MOSTLY (MAINLY) CLOUDY	For use when the amount of cloud is expected to be on the average greater than 5 tenths. However, there may be periods of as long as 5 hours when the cloud amounts is less than 5 tenths.
E) CLOUDY	For use when the predominant sky cover is expected to be between 5 to 7 tenths or more.
F) FREQUENT SUNNY (CLEAR) PERIODS	For use when the past sky condition has been predominately cloudy and (sunny) (clear) periods of up to several hours are expected.
G) FREQUENT CLOUDY PERIODS	For use when the past sky condition has been predominately sunny (clear) and cloudy periods of up to several hours are expected.
H) OVERCAST	For use when a complete cloud cover is expected over a significant period giving dull, grey conditions.

CHAPTER 3

MAXIMUM STAGE AT BREAKUP

Background Information

According to Shulyakovskii (1963), "ice cover drift and breakup on a river are usually the result of two processes: the melting of the ice cover....and an increase in the discharge and accordingly the flow velocities and rise of the river stage."

When sufficient discharge is produced to hydraulically lift the ice, fracture it, and propel it downstream, breakup is occurring. If ice jams occur at this time, the increased resistance to flow provided by the ice will increase the river stage, and may cause flooding. This increase of stage during a jam is evidently a function of both the discharge and the flow resisting properties of the jam-pack. It is presumed that the formation of a jam, and its resistance to flow, is related to the strength and thicknesss of the solid ice cover at breakup.

Meteorological parameters that might realistically be expected to describe ice thickness include degree days of frost (accumulated mean daily temperatures below 0° C over the previous winter), and snowcover, estimated from snowfall amounts, as an index of insulation and the potential formation of ice during the snowmelt period. Additionally, the reflective properites of snow protect the ice from exposure to the direct solar beam. Such parameters have been investigated in other studies. Gerard and Stanley (1986), however, could not find a relationship between either total winter snowfall or degree days of frost, and stage at breakup on the Yukon River at Dawson. Similarly, no relationship was found between either the snowfall accumulated between January and March or degree days of frost, and the maximum breakup stage on the Athabasca River at Fort McMurray (Fig. 15 and Fig. 16). These results are not surprising, as the influence of degree days of frost on ice thickness is diminished a short period after the initial freezeup due to the insulating effect of the ice cover. In the case of snowfall, the amount accumulated over this period tends to be both small and relatively consistent.

With the return of milder weather in the spring comes not only increased discharge, but river ice decay. A greater solar elevation, longer daylength, and higher

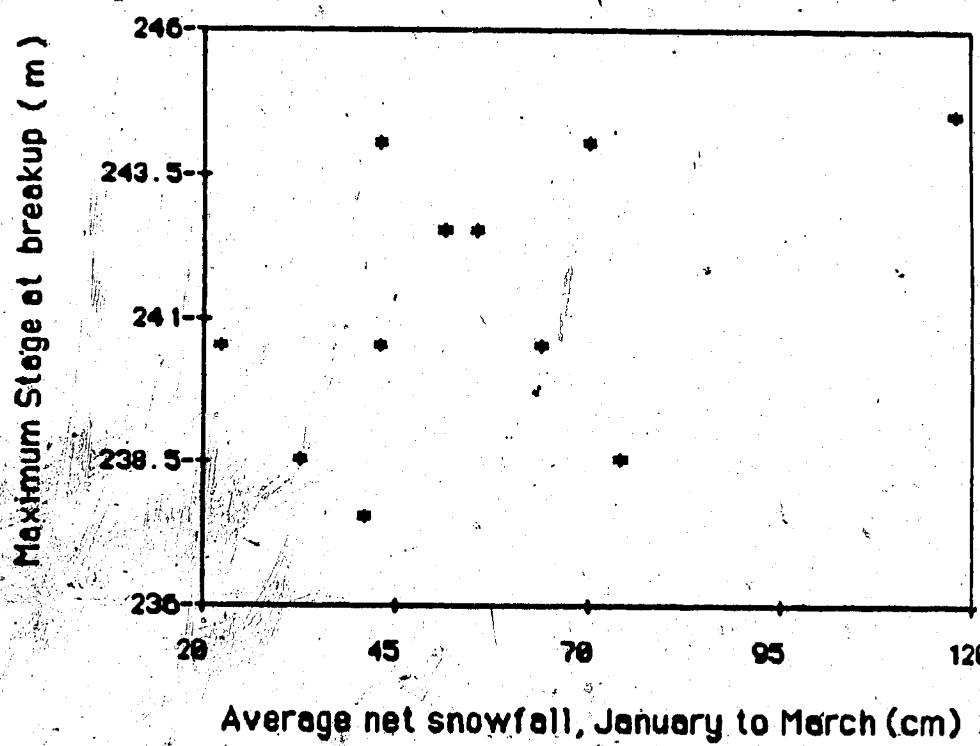


Figure 15 Relation between maximum breakup stage and antecedent snowfall for 12 years of record.

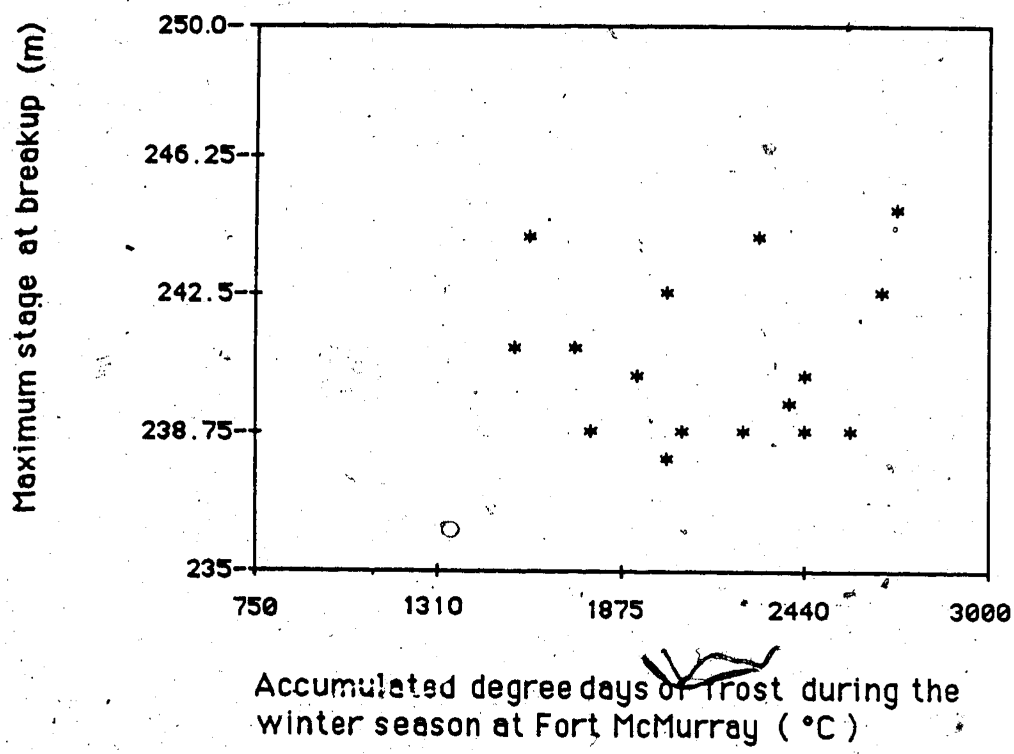


Figure 16 Comparison of the maximum stage at breakup to accumulated degree days of frost for 16 years of record.

temperatures all contribute to the breakdown of an intact ice cover. Above freezing temperatures and solar radiation act to ablate the river snowcover and eventually expose the ice to direct solar radiation. When so exposed, ice undergoes a decay process called candling, an internal weakening of the ice matrix along the crystal boundaries. As exposure time increases, the ice cover becomes progressively weaker, until finally it is easily disintegrated by impact, or simply decays in place.

Data Appraisal

Because of the small variation in ice thickness from year to year, and the expected close relationship of solar radiation to the strength of the ice sheet, it was decided to examine discharge at breakup and accumulated bright sunshine to assess their relation to the maximum breakup stage. As for Equation [illegible] [illegible]iod of accumulation was to be four days, in this case the 4 days before breakup, [illegible]as labeled T_{4S}. Several conditions had to be fufilled, however, before a valid [illegible]ge analysis could be undertaken.

Prerequisites before accumulating the hours of bright sunshine included the maintenance of daily maximum temperatures greater than or equal to 0 °C both prior to and during T_{4S}, since at or below that temperature, the snow cover on the ice would likely remain intact, and protect the ice cover from decay. The optimum length of the greater-than 0° C maximum temperature period was to be suggested by an examination of the data. By trial-and error, it was determined that a period of ten days of maximum daily temperatures greater than 0 °C had to elapse before commencing the accumulation of hours of bright sunshine, and is labeled T_{10}. This criterion is likely related to the mean time required for increased temperatures and radiation prior to breakup to completely ablate the snow cover on the river ice. Figure 17 illustrates a typical chronological relation between T_{4S} and T_{10}.

In years with little pre-breakup snow cover and a rapid onset of spring-like weather, perhaps this period of delay is excessive. However, as is evident in Table 8, no year of record from 1960 to 1985 experienced breakup until at least 13 days of maximum temperatures greater than 0 °C in succession had occurred. The discharge at

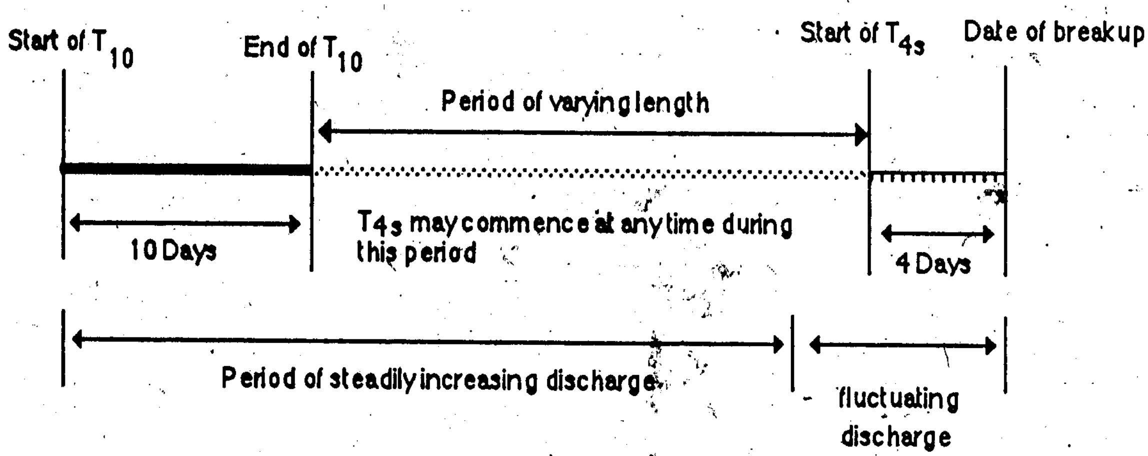


Figure 17 Illustration of typical pre-breakup chronology terminolgy

Table8 Length of pre-breakup period when maximum temperatures were greater than or equal to zero

Year	Length (days)	Comments
1984	25	Thermal breakup
1983	27	Thermal breakup
1982	19	
1981	18	
1980	26	Thermal breakup
1979	15	Severe jamming
1978	14	Actual period of thaw was longer, however it was interrupted by short periods where criteria were not met.
1977	13	Severe jamming
1976	20	
1975	19	
1974	15	Severe jamming
1973	23	
1972	13	Severe jamming
Mean	17.5	

breakup, as estimated through the use of Equation 1, and bright sunshine data for the years of record are given in Table 9, and are used to derive the following relationships.

Regression Analysis

A contributor to enhanced stage at breakup is the resistance to the flow provided by the ice in the channel. This resistance is assumed to be proportional to the thickness and internal cohesion of the ice (competence), and competence is in turn inversely proportional to the degree of internal decay that results, presumably, from exposure to shortwave radiation. If this assumption is valid, andd the initial ice thickness is the same from year to year, it should be possible to describe the flow resistance by an index of solar radiation. Figure 18 illustrates the relationship between maximum stage at breakup and accumulated hours of bright sunshine during T_{4S}. The trend is as expected.

Similarly, a component of stage increase can result solely from the usual enhanced flow at breakup, so that high stages can result from the greatly increased runoff often concurrent with breakup. Such a trend is evident in Figure 19. Hence, as expected, the maximum stage at breakup depends on both the discharge at breakup and the amount of radiation received prior to breakup. A relationship between the stage and these two parameters was therefore sought using regression. In the following analysis, ΔS is the stage in metres above zero-gauge datum at the WSC gauge a short distance downstream of Fort McMurray, Q and R the estimated discharge in m^3/s at breakup (from Equation 1) and the accumulated hours of bright sunshine throughout T_{4S} respectively, and α, β and ε are regression coefficients.

Two perspectives of the physical properties of breakup as related to stage increase were considered, Firstly, it was possible that stage was the result of the summation of effects of discharge and ice decay. In this case the increase in stage would be a linear function of the discharge plus a radiation- related factor that reduces the potential maximum stage as incident radiation increases. An equation of the form:

Table 9 Accumulation of bright sunshine in the four day period prior to breakup, and calculated change of discharge at breakup for 12 years of record.

Year	Calculated Discharge (m^3/s)	Four-day sunshine (h)
84	139	22.6
83	259	35.9
82	202	37.3
81	122	30.6
80	248	35.2
79	103	18.7
78	166	32.8
77	213	33.5
76	207	24.5
75	241	33.1
74	197	34.3
73	230	46.3
72	136	21.1

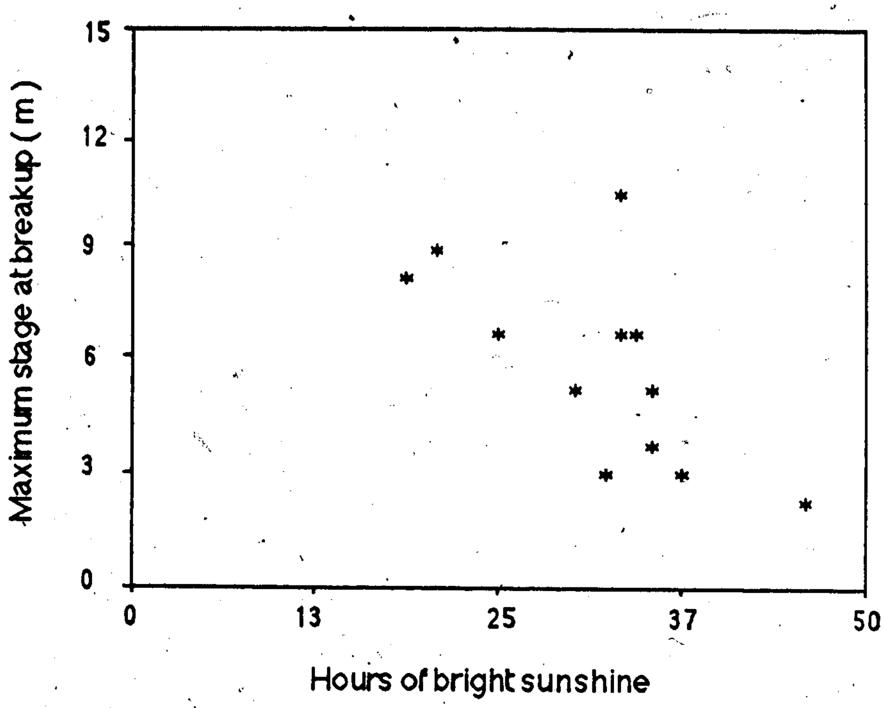


Figure 18 Relationship between maximum stage at breakup and accumulated hours of bright sunshine, four days prior to breakup at Fort McMurray

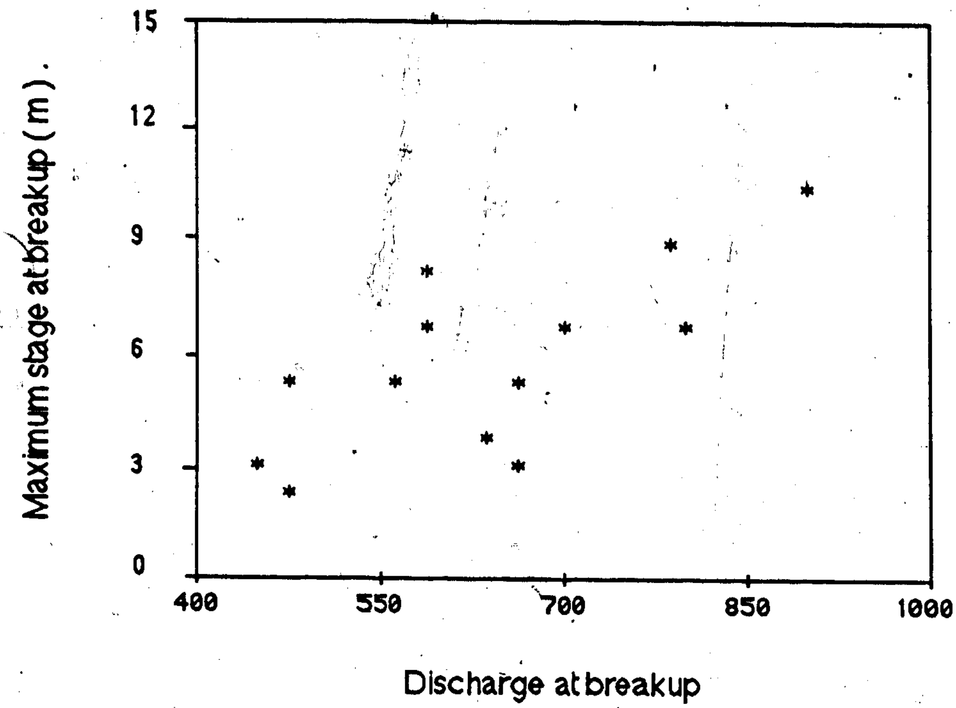


Figure 19 Comparison of maximum stage at breakup to discharge at breakup

(2) $$\Delta S = \alpha Q - \beta \Sigma R$$

should therefore be appropriate, where α and β are regression coefficients.

Secondly, the discharge could act in concert with the competence of the ice such that the maximum stage at breakup was a non-linear function of the product of the discharge and the inverse of the accumulation of hours of bright sunshine, so that:

(3) $$\Delta S = \alpha Q^{\beta} R^{-\varepsilon}$$

Three models, one linear and two non-linear were derived from the data. In the simple linear model, the best relation was given by:

(4) $$\Delta S = 0.0134Q - 0.0923 \Sigma R$$

This regression has a correlation coefficient of 0.81, and a standard error of estimate of 1.3 m.

In the first non-linear model, the exponents and coefficient were determined by regression, producing the relation:

(5) $$\Delta S = 0.15 Q^{1.06} \Sigma R^{-0.96}$$

with a correlation coefficient of 0.81 and a standard error of estimate of 0.90 m.

The Manning equation, used to describe uniform flow in standard hydraulics, suggests that, given constant hydraulic parameters, the mean depth, and hence approximately the stage, should vary as $Q^{0.6}$. A second non-linear model was therefore calculated by fixing the value of β at 0.6, resulting in one less degree of freedom, and the relation:

(6) $$\Delta S = 2.0 Q^{0.6} \Sigma R^{-0.875}$$

This relation has a correlation coefficient of 0.77 and a standard error of estimate of 0.93

m.

Figures 20 , 21 and 22 illustrate the respective performance of the three relationships when compared to actual values of maximum stage at breakup for 12 years of record.

Discussion of stage equations

When correlation coefficients between observed and predicted maximum stage are calculated purely on the basis of a small sample, for example, a few years of record as compared to the total population of all ice jams on the Athabasca River, any correlation may include a large element of chance. Additionally, the calculated correlation coefficient is only an estimate of the correlation coefficient for the population (Freund, 1982). A statistical test - the Fisher Z Transformation (described in Appendix C) - can be used to obtain confidence intervals for the mean correlation coefficient of the population, so providing an indication of the true strength of the relationship between model estimates of maximum stage and the observed values. If p is the actual population correlation coefficient, the 95% confidence interval of the correlation coefficient for (4) is $0.73 < p < 0.87$. For (5), $0.73 < p < 0.87$, and for (6), $0.68 < p < 0.84$. Clearly, there is little difference between the equations on this basis, as is directly evident from Figures 20 - 22. Of the two non -linear models, (6) has the marginally weaker relationship.

A statistical technique that measures the likelihood that two samples come from the same population, without the requirement that the samples have a normal distribution, is the Mann-Whitney U test (Appendix D). Essentially, the test determines if the null hypothesis -the supposition that the two samples come from identical populations- is acceptable. When the predicted maximum stage heights derived from the non-linear models are compared both to each other and the observed values, it is found that at the 95% significance level, the predicted and observed values have identical means, and are therefore drawn from identical populations. This also indicates the similarity of both non-linear models.

To corroborate this finding, the standard error of estimate given above were calculated as described by Higgs (1967). The standard error of estimate is the standard deviation of the residuals about a regression line, and is usually taken to represent a

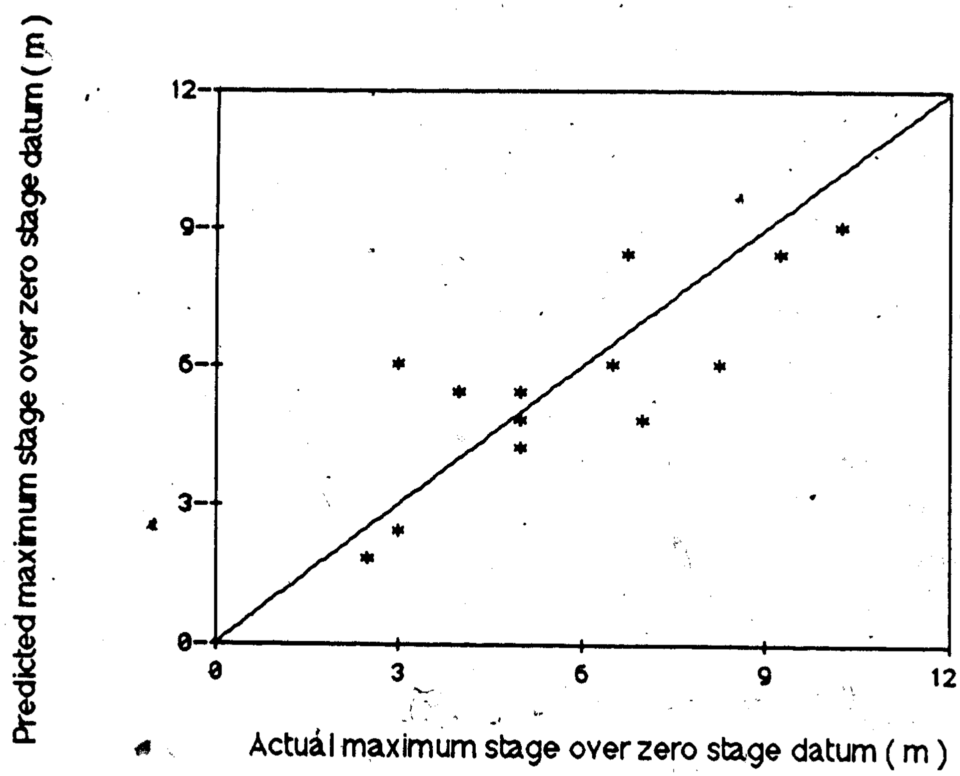


Figure 20 Performance of linear stage equation

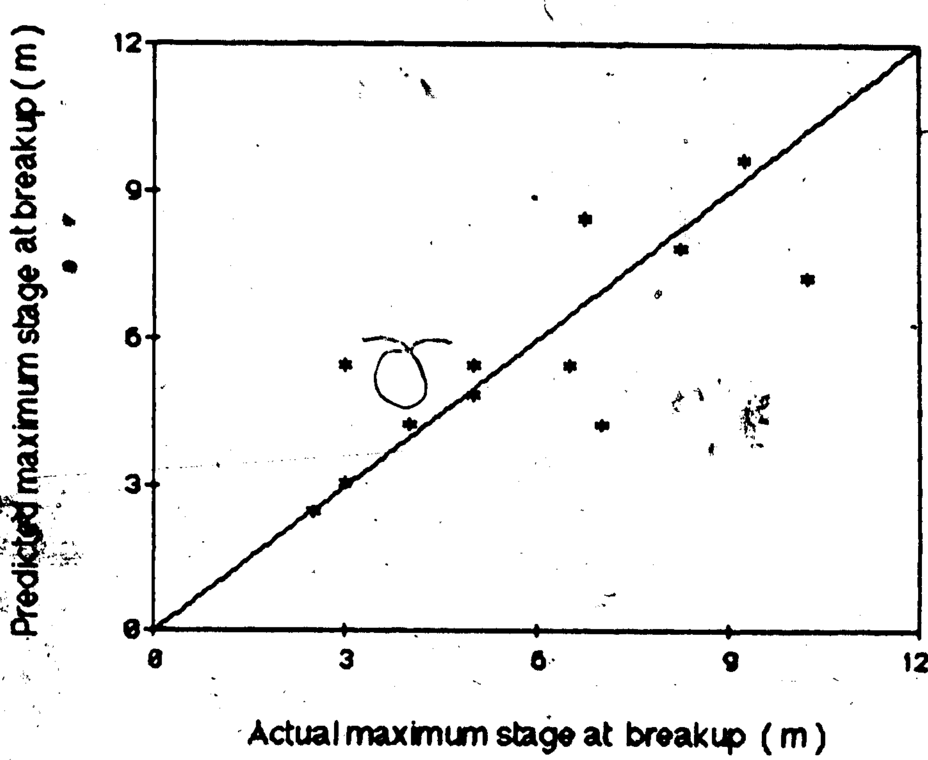


Figure 21. Performance of the non-linear stage model described by the function:

$$S = 0.15\,Q^{1.06}\,R^{-0.96}$$

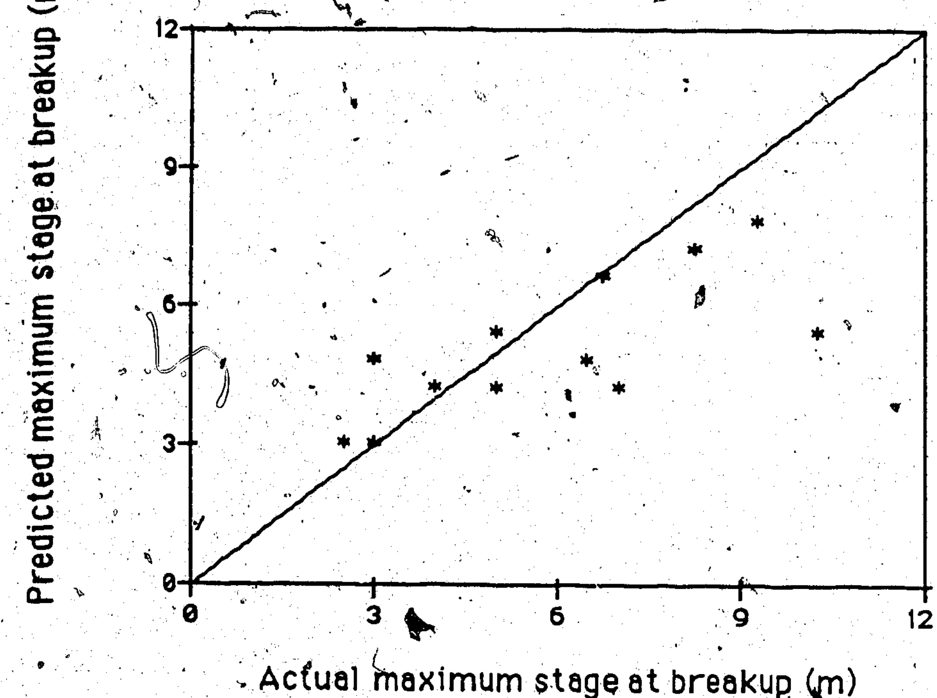


Figure 22 Performance of the non-linear model described by the function:

$$S = 2.0\,Q^{0.6}\,R^{-0.875}$$

measure of reliability of the regression. For the non-linear models, the standard error of estimate is similar, and the linear model has a standard error of es[illegible] somewhat inferior to both.

It is necessary that an equation be recommended to use to forecast stage at breakup. Because it has the lowest standard error of estimate, it is recommended that Equation (5) be used for forecast purposes.

A comparison of stage-related parameters and their time scales

Figure 23 illustrates the relationship between stage at break up and net hours of bright sunshine accumulated in the period between the completion of T_{10} and breakup, on a yearly basis.This relationship is similar to the one derived using T_{4S} and has, in fact, a better correlation. Unfortunately, the length of accumulation of bright sunshine varies from year to year as is expected, and often exceeds four days, and so a technique of maximum stage prediction using a long duration meteorological forecast of sunshine would not be practicable. It is apparent, however, that when the hours of bright sunshine accumulated in the interval after T_{10} but before breakup exceeded 45, stages in excess of 7.0 m above zero stage datum did not occur. There may exist a critical value of pre-breakup exposure to bright sunshine that will indicate, once exceeded, the reduced possibility of high stages occurring at breakup.

Figure 24 compares the maximum stage at breakup versus a ratio of the hours of bright sunshine accumulated after T_{10} but before T_{4S}, to those accumulated during T_{4S}. It is evident that years in which there is a large rise in stage have had a considerable fraction of their accumulation of bright sunshine in the four days prior to breakup. This indicates either that the interval between the end of T_{10} and the beginning of T_{4S} was a relatively cloudy one if longer than 3 or 4 days, or that it was short, say less than 4 days duration. From an examination of the meteorological record, it is clear that either explanation can be correct. In some cases of high stage at breakup, T_{4S} was comparitively "sunny" and produced considerable discharge, and the period prior to T_{4S}

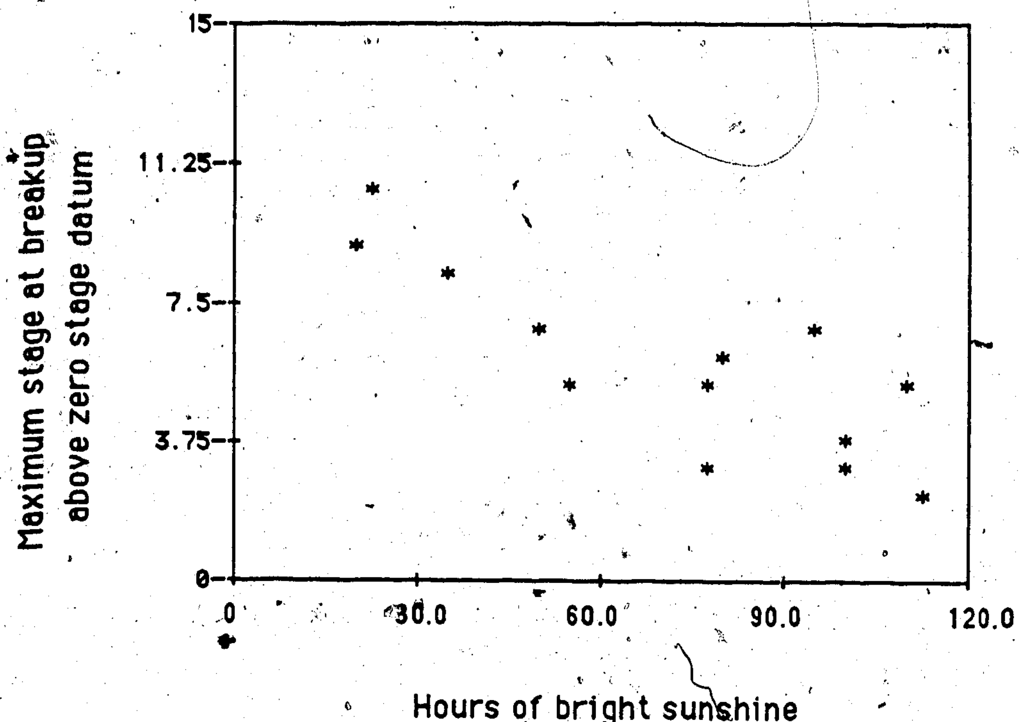


Figure 23 Relationship between hours of bright sunshine accumulated after T_{10} has elapsed, and breakup, and maximum breakup stage

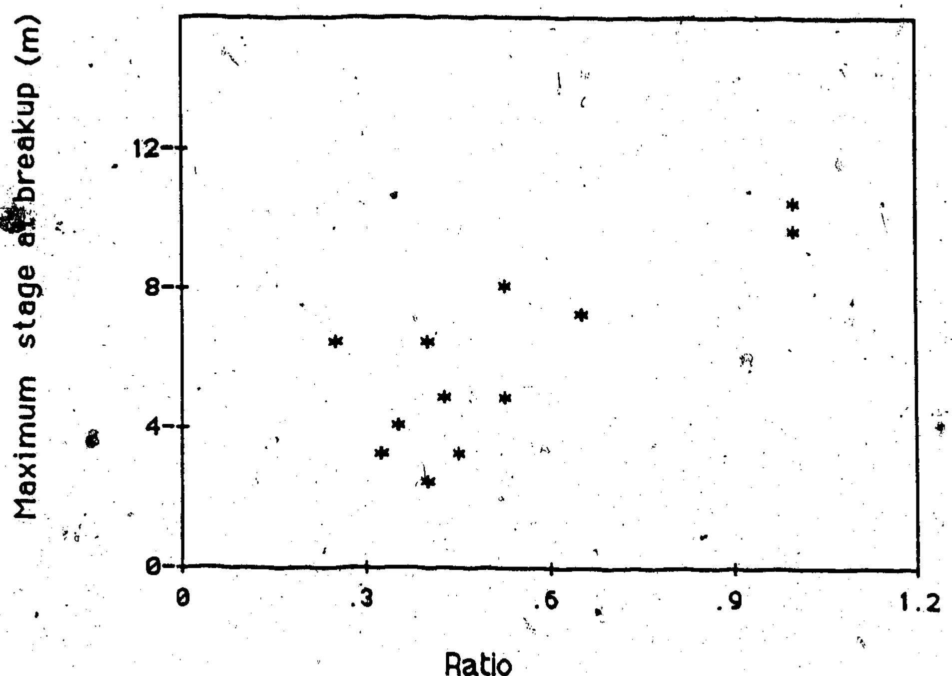


Figure 24 Ratio of bright sunshine accumulated during T4S to that accumulated after T10 has elapsed, to maximum breakup stage

was relatively cloudy; in other high stage cases, T_{4S} was a period of low solar radiation input, but the T_{10} - T_{4S} interval was very short, and so the ratio was high only by default. This strengthens the argument that high stages at breakup are governed by both solar radiation and discharge. Additionally, the ratio indicates that the decay of river ice is a function of solar exposure, as years with a low ratio generally experienced a longer period of exposure to bright sunshine prior to breakup than did high stage years, with the result that the ice *in situ* at breakup lacked sufficient competence to form a strong ice jam.

CHAPTER 4

TIME OF BREAKUP

Background information

In addition to forecasting physical breakup parameters, it is desirable to know when breakup is likely to occur, especially if, for example, the situation seems likely to result in flooding. To determine in advance a time of breakup, it is necessary to ascertain what characteristics of meteorology and hydrology are related to the time of breakup in a quantifiable manner.

A statistical analysis of breakup on the Athabasca River at Fort McMurray for 25 years reveals that the distribution of breakup dates is clustered about a mean of April 22, with a standard deviation of 5.8 days (Fig. 25). Based on the distribution of breakup dates during the period April 12 - May 02, breakup has about an even chance of occurring on any day in this interval. Such a simple statistical analysis does not, however, provide any insight into the meteorological and hydrological interaction involved in the timing of breakup.

It is clear that breakup is related to the decay of ice and the increase of discharge. A precise estimate of the time of breakup is, however, difficult to calculate since it is necessary to predict exactly when a combination of both sufficient ice deterioration and sufficient flow will coincide. Additionally, largely unpredictable pre-breakup surges in the flow may comprise the forces necessary to initiate breakup, provided the other parameters are conducive to such an event.

Data Appraisal

A simple index of ice cover deterioration - hours of bright sunshine - has been used previously to assist in the prediction of maximum stage at breakup. [illegible]en, discharge has been described by degree days of thaw and hours of brig[illegible]. Both indices, however, are calculated from observations measured over periods (4

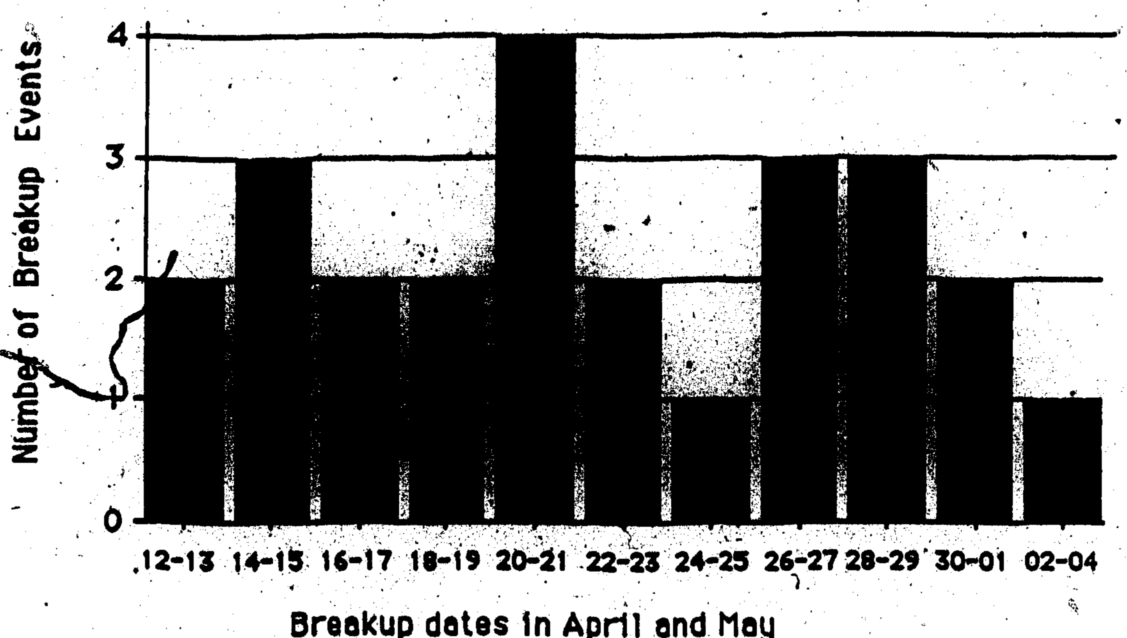


Figure 25 Distribution of breakup dates at Fort McMurray, 1960 - 1985

days) that are likely too short to be useful when applied to the timing of breakup, as the event seems to unfold in accordance with processes that have a longer evolution. It is clear that the accumulation of energy over a longer period, perhaps in the form of sensible heat and longwave radiation as described by degree days, bright sunshine prior to breakup, and a meteorological index of discharge should be considered in any attempt to determine in advance the date of breakup.

Table 8 provides the length of a period of mean daily temperatures greater than 0° C prior to breakup for several years of record, and a description of the type of breakup that ensued. An average length of this same period was termed a "critical period" by Thompson and Sporns (1964) in their study of breakup on the Liard and Hay Rivers, and was linked to the rate of downstream propagation of the flood wave.

No obvious relationship exists between the length of a period with mean daily temperatures greater than 0° C at Fort McMurray, and the time of breakup on the Athabasca at the townsite. It is clear, however, that the period of mean daily temperatures greater than 0° C is generally shorter than average for years in which there is a severe breakup, so that, as might be expected, breakup stage and length of the melting season at Fort McMurray are inversely related.

Analysis

A number of hydrometeorological parameters were hypothesised to be breakup-timing reated, and were tested by means of regression. Because the evolution of breakup was supposed, for purposes of this study, to be a long-term event, meteorological parameters were evaluated for their relation to the timing of breakup over the interval bounded by the commencement of steadily increasing flow, and the date of breakup. The only promising relationships between the length of the pre-breakup period and the variables include the two linking the rate of accumulation of bright sunshine on a daily basis, and the rate of change of discharge. The connections between the two are rather weak, however. Additionally, both of these quantities are averaged over the entire period, and so do not provide any explicit indication of the day-to-day physical process involved.

Discussion

To summarise that which is known about the timing of breakup, no breakup has occurred before a minimum of: 86 hours of bright sunshine, 15 consecutive days of steadily increasing discharge with a minimum net accumulation of 0 °C degree days of thaw, 13 consecutive days of mean daily temperatures greater than -5° C with a minimum accumulation of 17.1 degree days of thaw, and 4 days of mean daily temperatures greater than 0° C with a minimum accumulation of 13.9 degree days of thaw have been recorded at Fort McMurray in the 1972 - 1984 period. For all years of record, the daily mean temperature has varied, but remained above 0 °C for at least several days before breakup. During this period, breakup has occurred approximately 3.5 days after the mean temperature peak with a standard deviation of 2.4 days.

Presumably, the rate of accumulation of the meteorological and hydrological variables are related to the synoptic meteorology over Fort McMurray, and hence much of the Athabasca River basin during the melting period. A good indicator of the likely severity and timing of timing of breakup may therefore be found by an examination of both local and regional meteorological conditions, at both the surface and aloft, during the pre-breakup period.

CHAPTER 5

SYNOPTIC METEOROLOGY AND BREAKUP

Background Information

Relations between local hydrometeorological parameters and ice jam formation have been derived empirically from surface climate data at the Fort McMurray weather office during the breakup period. Such relations do not, however, provide information about how the basin is "primed" for breakup, or under what long-term conditions of meteorology breakup will occur, nor do they give an indication of more general hydrometeorological patterns under which breakup severity will vary. The utility of the above relations for the forecast of breakup is therefore limited.

Some additional shortcomings of locally derived breakup relationships, pertaining to the the period of spring melt, include the meteorological aspects of the scales used. Weather can vary dramatically about a normal climate during short periods as the seasons progress, and over relatively small changes in horizontal distance and elevation. The data obtained from a single station may therefore be quite unrepresentative of even nearby stations. In data-sparse areas such as the area of study, local orographic influences may, for example, change the mean daily cloudiness over small areas in adjacent regions and so affect the cumulative solar exposure. Hence, without a broader knowledge of the larger scale, or synoptic meteorology during the breakup season, the utility of a forecast of breakup parameters is tenuous at best. By conducting a meteorological analysis of such parameters as temperature and cloudiness, both at the surface and at a sufficient altitude to eliminate local effects, and by extrapolating observed and forecast conditions to the surface, more general statements concerning the meteorological aspects of breakup can be derived, and the conditions that are conducive to the inception of breakup can be predicted.

Comparison of the locally observed meteorological aspects of breakup to the synoptic regime

An examination of the daily temperature record reveals that, in general, approximately half of the degree days accumulated between the start of increasing discharge and breakup are accumulated in the week prior to breakup. As the mean length of the period of increasing flow is 20.4 days (for 12 years of record), it is probable that a period of elevated temperatures typically occurs during a short period a few days prior to breakup, and may in fact be a condition for breakup.

Figure 26 indicates the mean temperature trends for 25 years of record, from two weeks prior to breakup, to two weeks after the event, divided for purposes of comparison into those with a severe, and non-severe breakup. A severe breakup is defined as one resulting in some flooding of the Fort McMurray townsite, and has occurred in 1962, 1963, 1972, 1974, 1977 and 1979. There are several differences between the mean temperature trends of severe breakup versus non-severe breakup years. From 14 to 10 days prior to breakup, the mean temperature for severe breakup years ranges from 2 - 5 °C lower than that calculated for non-severe breakups. Both trends do, however, show some similarity insofar as the general trend evident at this time is toward rapidly increasing daily mean temperatures (approximately 8 °C in 8 days). From 9 - 6 days before breakup the trend reverses, with the severe breakup years of record generally experiencing mean temperatures higher than the non-severe breakup years. The final 5 days prior to the debacle are characterised by lower mean temperatures for the six severe breakup years.

The trends of mean daily temperature apparent in the plot must be interpreted with some caution, as the standard deviation of daily mean temperatures in April at Fort McMurray is 3.3 °C (AES, 1981). Several inferences may nevertheless be made from the apparent temperature trends. Firstly, the rapid increase of mean temperatures in the initial period of measurement likely indicates the north-ward progression of the Continental Arctic (cA) Front -a line of demarkation indicating the positions of the cold, continental air to the north of the front, and warmer air of maritime origin to the south- and its encroachment into the north central Alberta area. Figure 27 illustrates the usual seasonal position of the Arctic Front. For both severe and non-severe breakups, this is

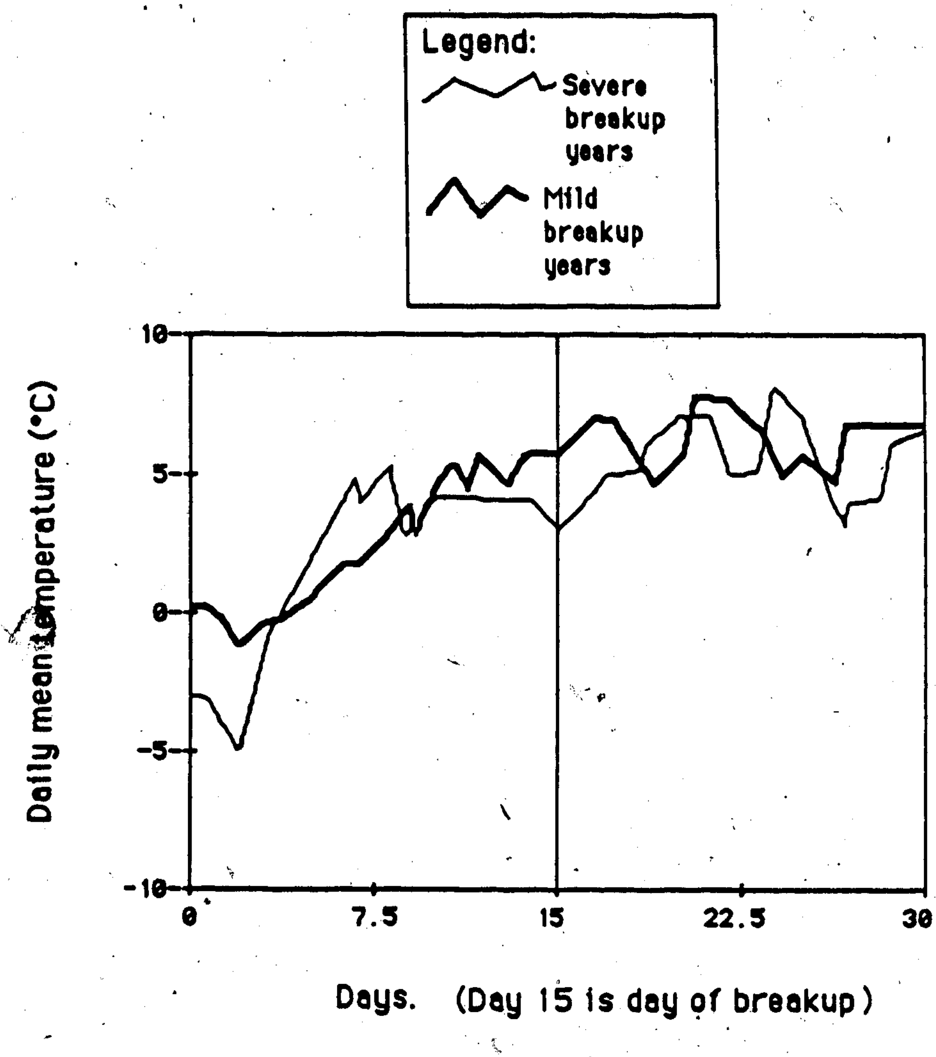


Figure 26 Comparison of daily mean temperatures, two weeks before to two weeks after breakup, for severe and non-severe breakup years, for 25 years of record

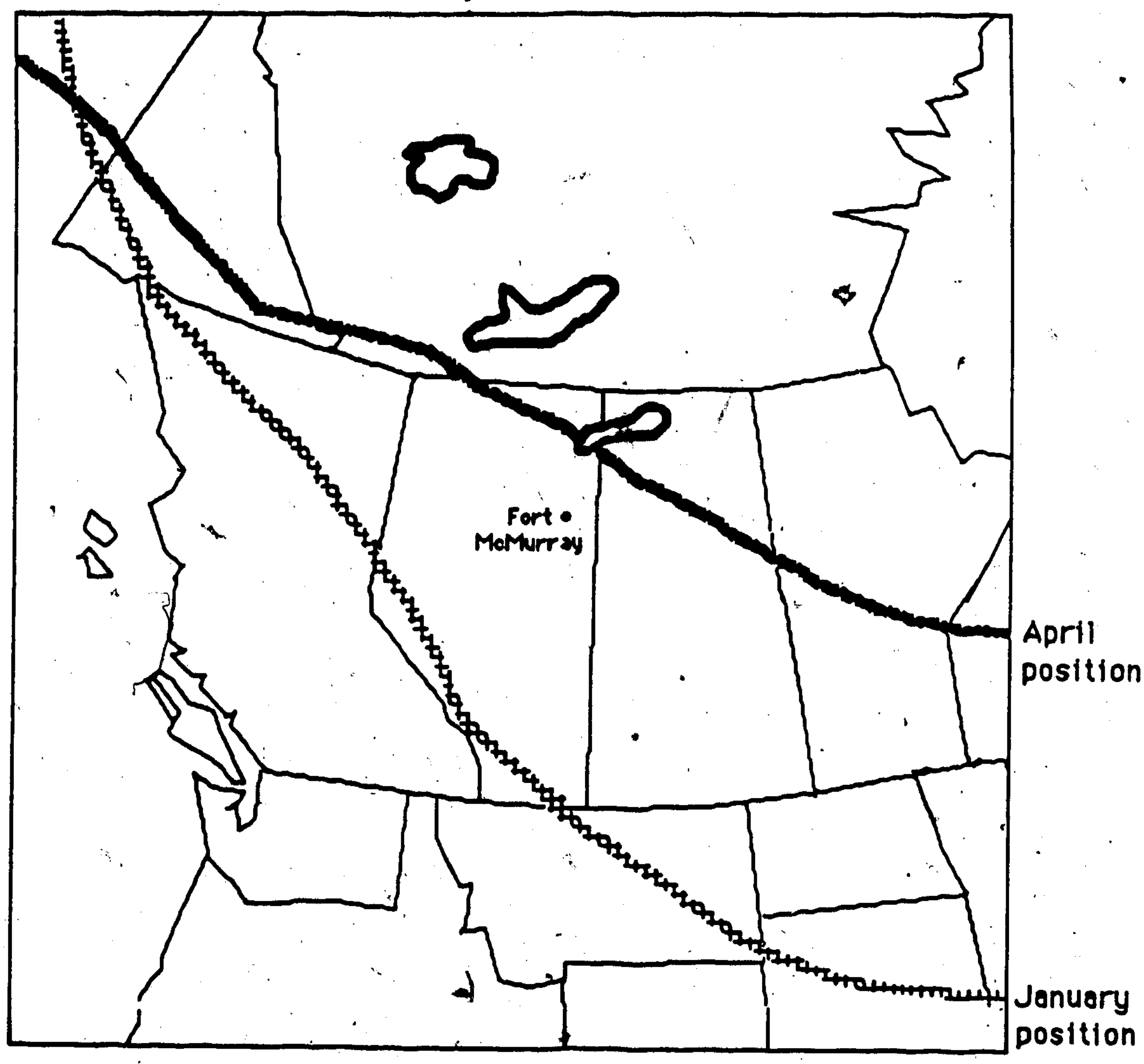


Figure 27: January and April mean positions of the arctic front.
(modified from Chang, 1972)

the clearest precursor of breakup, and is indicative of a change in the general upper-atmopheric flow regime, as will be examined later. Secondly, as short-wave disturbances have a tendancy to form on, and propagate in a generally easterly direction along the cA front, it is likely that the Fort McMurray region, when in the vicinity of the recently arrived front, will experience temperature fluctuations with a period proportional to the propagational speed of the disturbances on the front, or say, every 2 or 3 days.

To summarize, the typical synoptic evolution during the breakup period is characterised by the arrival of the cA front at Fort McMurray and environs in the 14 to 7 days prior to breakup, followed by approximately a 1 week duration of fluctuating temperature and bright sunshine conditions. For years of record in which a severe jam has occurred, the week prior to breakup was typically cooler than the same week for the non-severe breakup years.

Temperature trends are, however, not the sole means of inferring meteorological conditions on the synoptic scale. An examination of the records of bright sunshine during the 4 weeks preceeding breakup reveals what, on first inspection, would seem to be a paradox: that the proportion of total sunshine received during the last week of a four-week period prior to breakup for severe breakup years is greater than the proportion of sunshine received during the same period for non-severe breakup years, even though the years with a severe breakup are cooler, on average. Table 10 provides a comparison of the proportionality of hours of sunshine accumulated in the four weeks prior to breakup inclusive, versus that accumulated in the last week before breakup, for severe and non-severe breakup years. Those years with severe breakups have, in general, a higher ratio. One interpretation of the ratio is as follows: a "low" ratio, that is one of about 0.25 or less, implies a steady and consistent period of daily sunshine over the entire period, or perhaps the occurrence of a cloudy final week before breakup. A "high" ratio, that is one greater than 0.25, suggests either extensive cloudiness in the three weeks prior to breakup, with "normal" sunshine duration thereafter, or that a rather more sunny period occurs in the week just prior to breakup.

In the case of severe breakup years a detailed examination of the week prior to breakup indicates that the above interpretation is not entirely correct. It is not a single

Table 10

Hours of Solar Radiation at Fort McMurray for the four week period prior to breakup and for the week prior to breakup, categorised by years in which an ice jam flood ocurred at breakup, and those years when no flood ocurred, and ratio of 1 week to 4 week accumulation, 1972 - 1984.

Flood years

Year	4 week sunshine (h)	1 week sunshine (h)	Ratio
1972	187.3	64.7	0.345
1974	192.3	73.8	0.384
1977	200.7	61.5	0.306
1979	144.8	60.3	0.416
Mean	181.4	65.1	0.359

Non-flood years

Year	4 week sunshine (h)	1 week sunshine (h)	Ratio
1973	239.3	65.7	0.275
1975	187.7	53.2	0.283
1976	217.4	53.1	0.244
1978	173.4	36.7	0.212
1980	234.3	74.0	0.316
1981	190.9	47.2	0.247
1982	200.7	70.0	0.349
1983	200.4	55.4	0.277
1984	162.8	30.1	0.185
Mean	200.8	53.9	0.268

type of weather that preceeds a severe breakup, but rather two somewhat different weather types. The first type is that characterised by considerable sunshine in the week or so prior to breakup, but with close to average sunshine over the four week period. This describes the 1977 and 1974 breakups. A more detailed examination of the mean temperature record for the week prior to breakup reveals that, for the first type, the final 2 or 3 days before breakup bring a return to cloudy and cooler weather, hence most of the sunshine occurs in the first half of the week prior to breakup. The second type has relatively low values of sunshine during the entire four week period prior to breakup, but similar to the first type, has a large fraction of the total sunshine occuring in the week prior to breakup, and is representative of the 1972 and 1979 breakups.

The above discussion suggests the severity of breakup is influenced by the meteorological conditions that occur in the day or two prior to breakup. If this is so, an examination of those conditions may indicate the nature of the response of the breakup regime to potentially classifiable types of weather that occur just prior to a severe breakup.

A simple method of determining the general characteristics of surface synoptic conditions is to examine the conditions aloft, above the direct and multifarious influences of the surface. For this, some understanding of the general circulation is required.

FEATURES OF THE GENERAL CIRCULATION

The general circulation consists of the average motion of the atmosphere, examined over a sufficicent period to determine a mean flow pattern. Within the general circulation, certain meteorologically relevant fields are shifted, altered and transported about the atmosphere in accordance with known physical laws and relationships, and so in a somewhat predictable manner.

An important atmospheric field that is transported by the general circulation is atmospheric "thickness". The thickness of a layer of atmosphere between two constant pressure surfaces is proportional to the mean virtual temperature of that layer. In the absence of data regarding the mean thickness of a layer, the "height" of a constant pressure surface provides a reasonable substitute. Height is defined as the vertical distance above sea level of a constant pressure surface, and so the 500-mb height is therefore the 1000-mb height - the height of the 1000 mb surface above or below mean sea level, added to the 1000-500 mb. thickness. In general, the 500- mb height field of a region correlates well with the 500 - 1000-mb thickness field (Figure 28) (Wallace and Hobbs, 1976).

An empirical equation has been derived, correlating 850-mb temperatures with 500-mb height and 1000 - 500-mb thickness (Kagawa and Jarvis, 1968). Of course, extrapolation of 850 mb airmass properties to the surface as a means of determining surface temperatures requires some information regarding the mixing characteristics. Nevertheless, the 850 mb temperature is a useful indicator of the potentially attainable surface temperature. The major portion of the Athabasca River basin is located beneath the average 850-mb contour. The usefulness of their method will not be examined in this study, however.

Upper-air high-pressure areas or ridges, which have greater heights than adjacent regions of lower pressure, are generally associated with clearing and elevated temperatures upon their arrival over a station. An upper flow regime directing upper high pressure, or greater thickness, toward a region of upper low pressure, or relatively lesser thickness, is said to be horizontally transporting, or "advecting", positive thickness, ie. higher mean temperatures, to that region. Ridges aloft are normally associated with warm air advection at the surface (Chang, 1972).

One simple method used to determine the type of flow at upper levels, with regard to a surface station, is the 500-mb height anomaly- that difference from the meteorologically normal height for a particular date (Nimchuk, 1983). A significant positive anomaly usually indicates the presence of a ridge; a significant negative anomaly an upper trough.

Previous Studies

A few investigators have attempted to use upper flow data as indicators of ice jam conditions. McMullen (1960) linked an abrupt change from a persistent northerly, hence cold, flow at the 700 mb level, to a predominately westerly flow with the

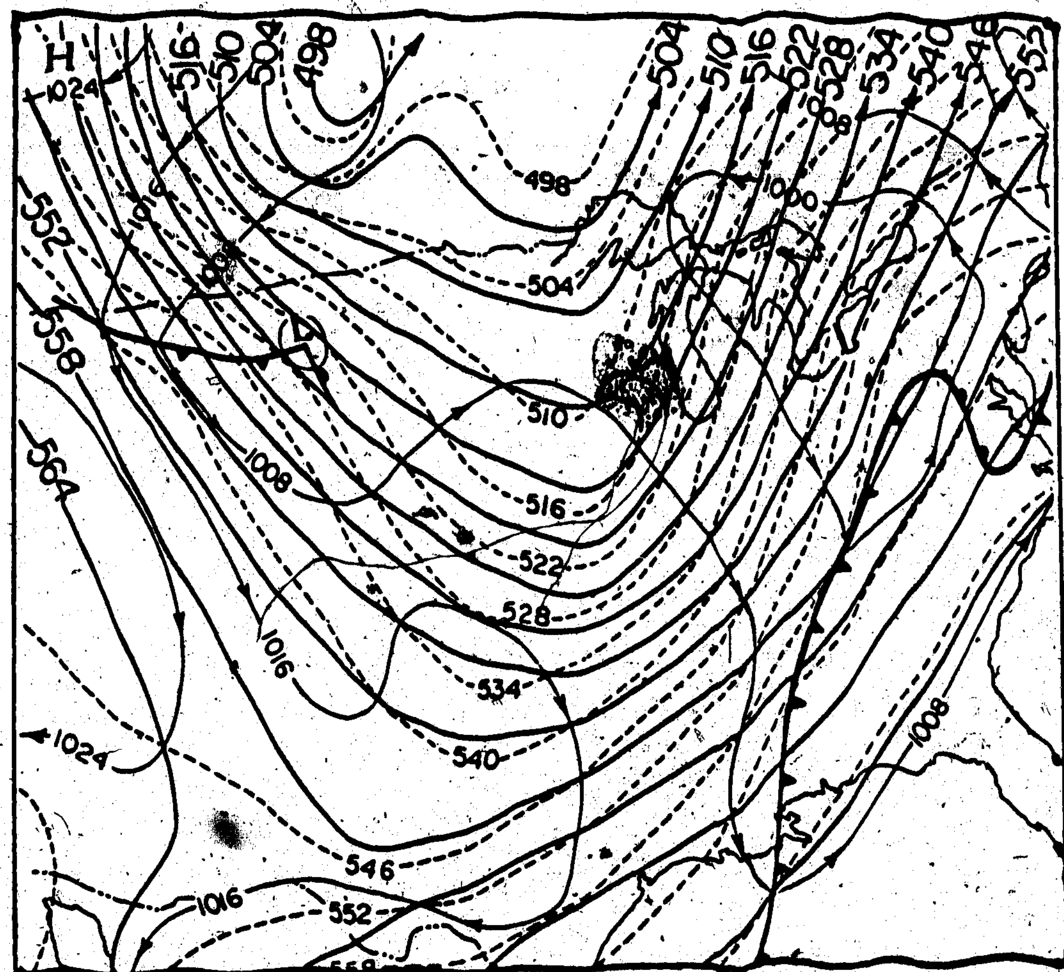


Figure 28 Adapted from Wallace and Hobbs, 1976. Relation of sea level pressure ⟶ 500-mb height ——— and 500 - 1000-mb thickness ·······

Thickness and height contours in 10's of metres.
Arrows on sea-level pressure isobars represent geostrophic wind direction

subsequent rapid breakup of the Thames River in southwestern Ontario. As illustrated in Figure 29, a considerable warm-air advection into the region over a two day period was associated with the flow pattern shift. A vigorous snowmelt and rapidly rising water levels resulted in a forced breakup. It was claimed that a forecast of expected changes in the upper atmospheric flow could be of great use in the forecasting of breakup during springtime.

Severe ice jams and coincident flooding at breakup on the Liard River in British Columbia and the NWT were shown to result from an above-average temperature and solar radiation regime for a three-week period prior to breakup in April, 1963 (Thompson and Sporns, 1964). The establishment of a persistent upper ridge at the 500-mb. level in mid-April initiated and perpetuated the mild and sunny conditions required for the rapid melt of an above average snowfall in the basin (Fig. 30). Additionally, nearly 150% of normal bright sunshine was recorded in the basin over the period of ridge persistence.

Henry (1965) claimed that a forecast of "no flood" for the Yukon River in Alaska could be made on the basis of a 30-day outlook and a 5-day forecast of the upper flow for the Gulf of Alaska region. The location of the quasi-permanent upper-air trough in the Gulf determines where melting conditions in the Yukon River basin will occur in spring-time. If, for example, the trough is well established in the Gulf, and persists throughout the latter part of April and into early May, the headwaters region of the basin will produce considerable melt while the ice in the middle and lower sections of the river remains competent. Conversely, the presence of a major ridge at the same location and time, with its enhanced temperatures and sunshine, will result in a breakup of the lower stretches of the river before the arrival of the headwater melt, thus avoiding jams.

Savchenkova (1972) derived an index of atmospheric circulation for the European territory of the Soviet Union, based on the mean flow pattern for a particular period -usually defined as a "season". Essentially, 100 stations in the area under consideration were geographically designated as either "eastern" or "western". The difference between the monthly average height of the 500-mb surface of the western and eastern stations comprised the index. When the circulation is zonal, the index should be nearly zero; during a meridional circulation, the index has some positive or negative value. If positive, the western region has a greater mean geopotential,

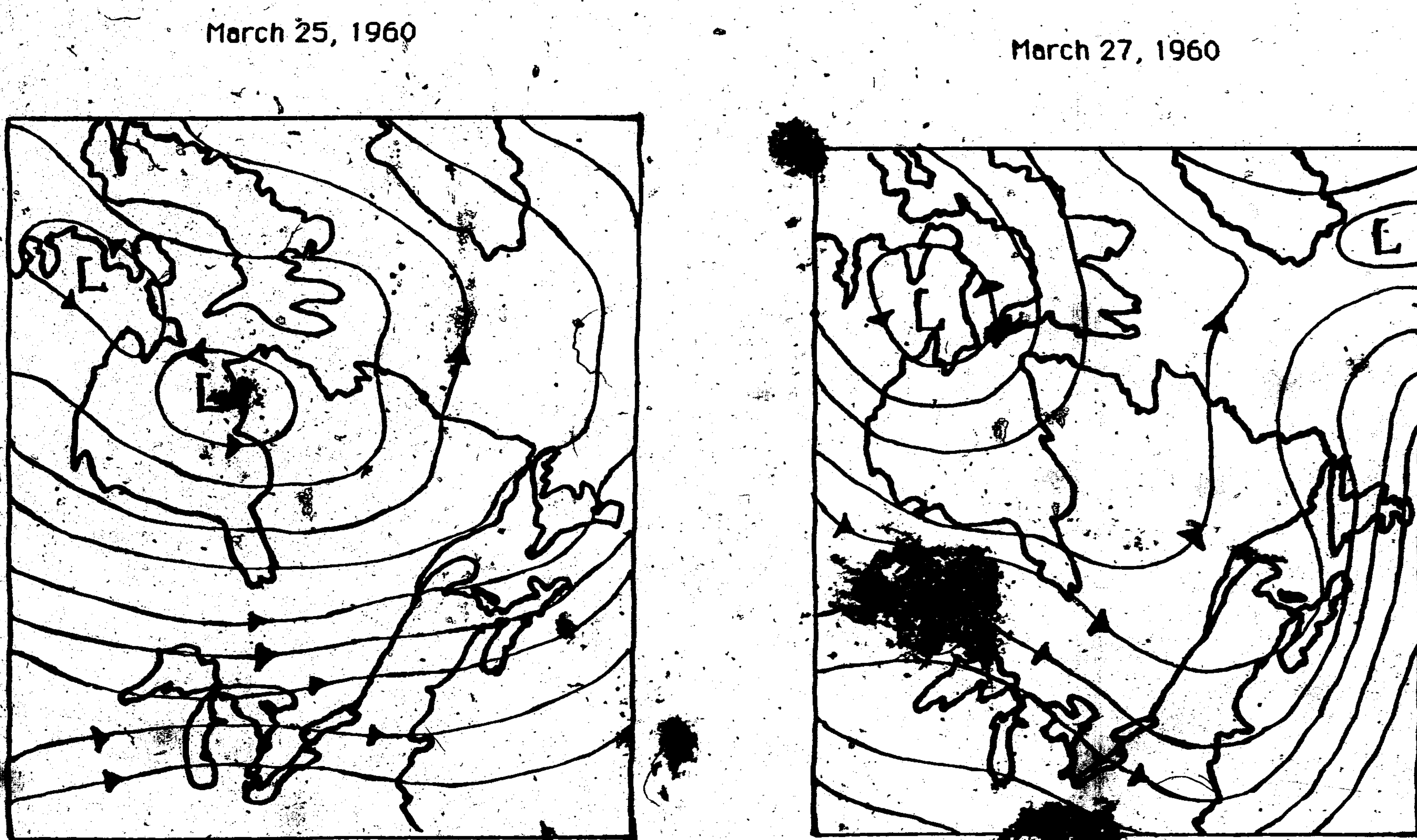
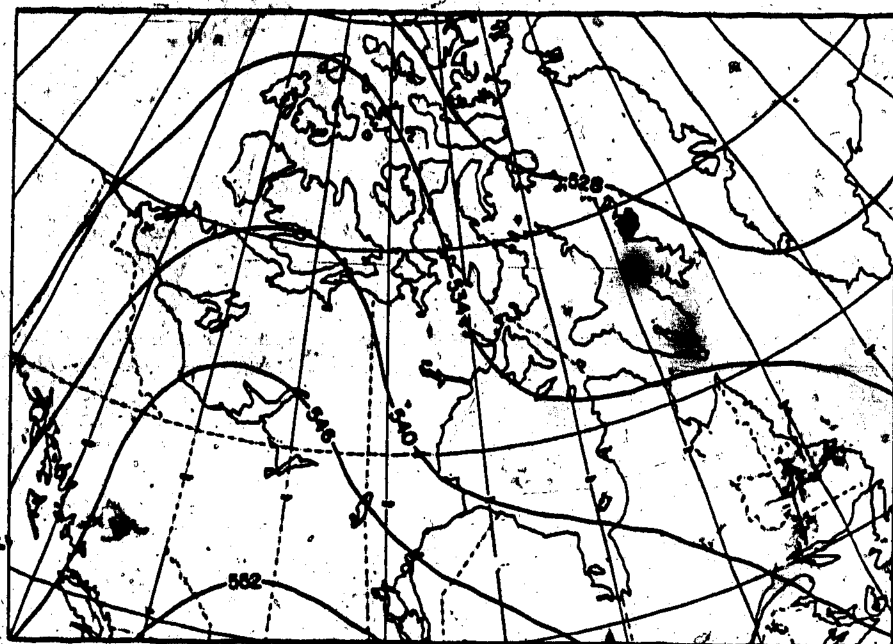
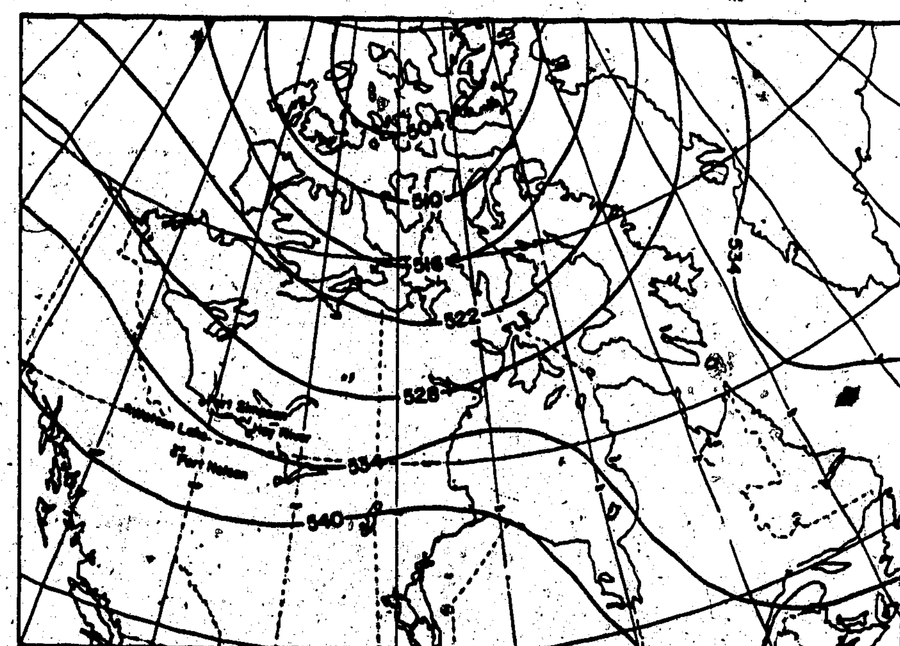


Figure 29 Adapted from McMullen (1961). Alteration [illegible] 700 mb flow pattern prior to breakup on th[illegible] River near London, Ontario, 1960

Solid lines with arrows represent mean 700-mb height contours.



MEAN 500MB CHART - APRIL 11-30, 1963



MEAN 500MB CHART - APRIL 1-10, 1963

Figure 30 Adapted from Thompson and Sporns, 1964. Alteration in the 500-mb flow during the month of April.

Solid lines represent 500 mb contours in 10's of metres indicating the existence of either a ridge over the western region, a trough over the eastern section, or both. A large positive index indicates the presence of a strong western region ridge, with associated cold-air advection and lower thickness into the eastern section, and hence delayed eastern region river breakup dates.

This technique was used to forecast the breakup of rivers in the north-eastern Soviet European territories. Figure 31 illustrates the correlation between the circulation index and the date of breakup. The vertical axis represents the date and month of breakup, and the horizontal axis represents the value of the circulation index. The diagonal lines indicate confidence intervals; however their value is not revealed in the text. Superimposed on the plots is the year of breakup. Based on a 15 - 45 day advance forecast period, the correlation coefficient of the regressions is 0.71 to 0.93.

A more sophisticated system to forecast the nature of breakup from meterorological conditions was devised by Fogarasi (1985). A scheme to categorize standard weather patterns and their influence on the evolution of breakup was developed for the Liard River basin in the NWT, based on the vertical profile of the potential wet-bulb temperature obtained from daily radiosonde ascents at Fort Nelson, British Columbia. Essentially, the potential wet-bulb temperature is a conservative atmospheric property, so that even if an airmass rises or descends adiabatically, and condensation or evaporation occurs, such as in orographic rainfall or a chinook, the potential wet bulb temperature is nevertheless maintained (Iribarne and Godson, 1973). From this property one can determine the origin of the airmass overhead regardless of the adiabatic transformations it may have undergone, provided non-adiabatic effects are minimized while the airmass is in transit. Knowledge of the origin of the air helps to predict its meteorological characteristics, and to identify the probable upper flow pattern. In addition, several conclusions can be drawn regarding the state of the atmosphere from the appearance of the vertical profile of wet-bulb potential temperature, such as vertical energy exchanges (mixing), advection and the persistence, when averaged over time, of a particular weather pattern.

A vertical profile consistent with mixing will indicate the exposure of the surface to the pattern aloft. A warm, well mixed air-mass in the basin will result in snowmelt. Conversely, an inversion may be discerned by an examination of the profile, and will indicate the prevention, by atmospheric stability, of an energy transfer to the surface,

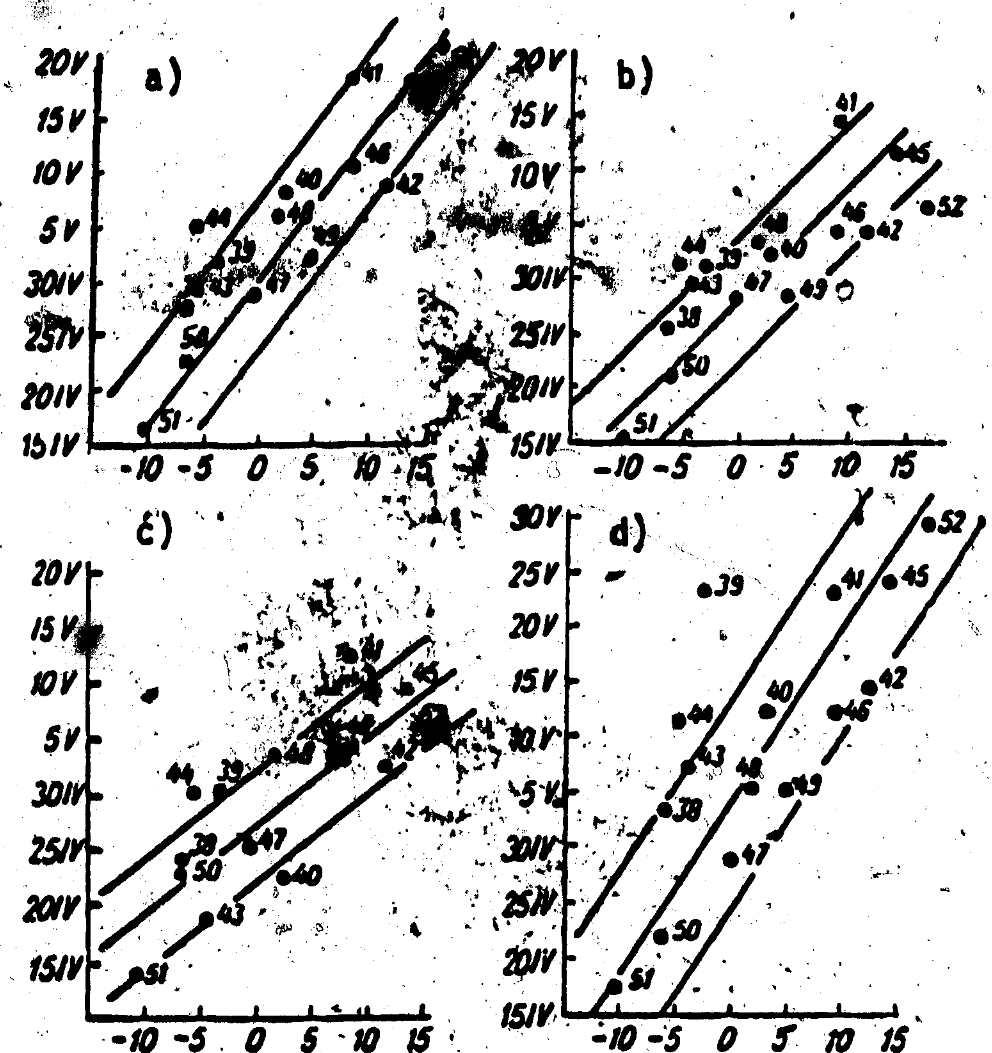


Figure 31 Relation of circulation indicies and the timing of breakup for four rivers in the Soviet Union (adapted from Savchenkova, 1972)

The horizontal axis is labeled with the value of the circulation index (dimensionless)

The vertical axis is labeled with date and month (IV = April)

The data are labeled with the year of particular breakup (43 = 1943) thus reducing the probability of snowmelt. Figure 32 illustrates two typical vertical wet-bulb potential temperature profiles classified by Fogarasi. Table 11 provides a summary of the meteorological conditions, and snow melt potential associated with each profile, and Figure 33 illustrates the typical state of the 700 mb flow observed in conjunction with each class.

From the above investigations, it is clear that some patterns of the upper flow are associated with the inhibition of breakup, others promote it, and a few are neutral. Those patterns indicating a large-amplitude, high-thickness ridge over a region in the springtime are associated with thickness advection with resulting increasing warmth and clear skies and hence enchanced snowmelt. Troughs are, at this time, associated with cloudiness and reduced temperatures and hence with breakup delays; the length of delay corresponding to the persistence of the feature. Both troughs and ridges transport air in a 'meridional' manner, or in a direction along the meridians.

Flow in a direction parallel to lines of latitude, or 'zonal' flow, is associated with a minimum meridional transport of air, and hence no drastic warming or cooling, but rather with either the maintenance of existing weather, or the moderation of extreme conditions. Although not a distinct category of Fogarasi's, such a flow regime in the breakup season may either accellerate or delay breakup, depending both on the prior flow and the lateness of the season. Early in the breakup period, zonal flow should generally provide higher than normal temperatures, as it will bring, to the major part of the basin, relatively milder Pacific air. Toward the end of the season, zonal flow should delay breakup, since the Pacific air will, by this time, be relatively cooler than the seasonal normal.

An examination of the 500 mb flow, hence the features of the general circulation, over the Fort Mcmurray region during the breakup period should reveal the characteristic flow patterns associated with breakup, if any. In addition, it is hoped that the following cursory analysis of the atmospheric flow over the four day forecast period used for the previous stage and discharge models will indicate whether the imminence of breakup can be determined by conditions aloft.

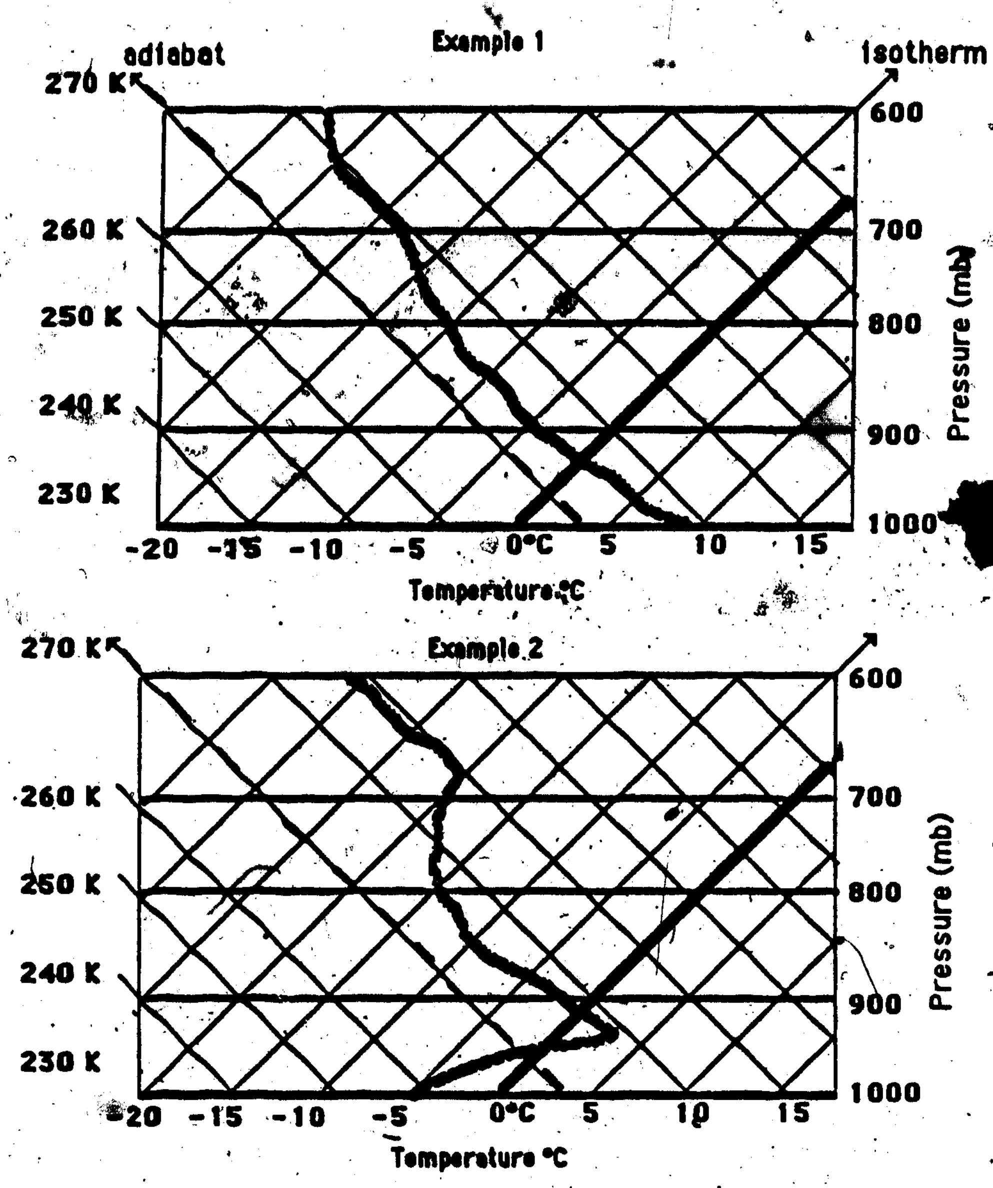


Figure 32 Adapted from Fogarasi, 1984. Tephigrams used to determine the breakup -related energy transfer properties about the breakup period.

—Vertical dry-bulb temperature profile.
Example 1 illustrates a well-mixed lower atmosphere. Example 2 illustrates a strong inversion with little mixing at the lower levels

Table 11 Descriptions of weather associated with upper flow classifications relating to breakup (adapted from Fogarasi, 1984)

Pattern	Range of Surface temperature from RM	700 mb mean synoptic pattern	Possible processes between Sfc-900mb	900-800 mb	General conclusions
E1	-1σ - +1σ	ridge	cold advection radiation subsidence	same clear subsidence	slightly favours snowmelt
A	-1σ - >+1σ after Apr. 5 always >0° C	ridge	Warm advection	same inversion	favours snowmelt
D	-1σ - +1σ	ridge	radiation no advection	advection varies	warmer than RM in second part of Apr.
B	-1σ - RM	variable small gradient	no advection radiation turbulent transfer	same same	cooler than RM in Apr.
AE	RM - >+1σ	ridge	no advection radiation	same subsidence	promotes snowmelt
C	<-1σ - RM always cold	NW arctic flow	warm advection negative energy budget	same overcast flurries	delays breakup
-D	-1σ - RM	trough	radiation no advection	ascending flow cloudy	delays breakup

note: RM = running mean

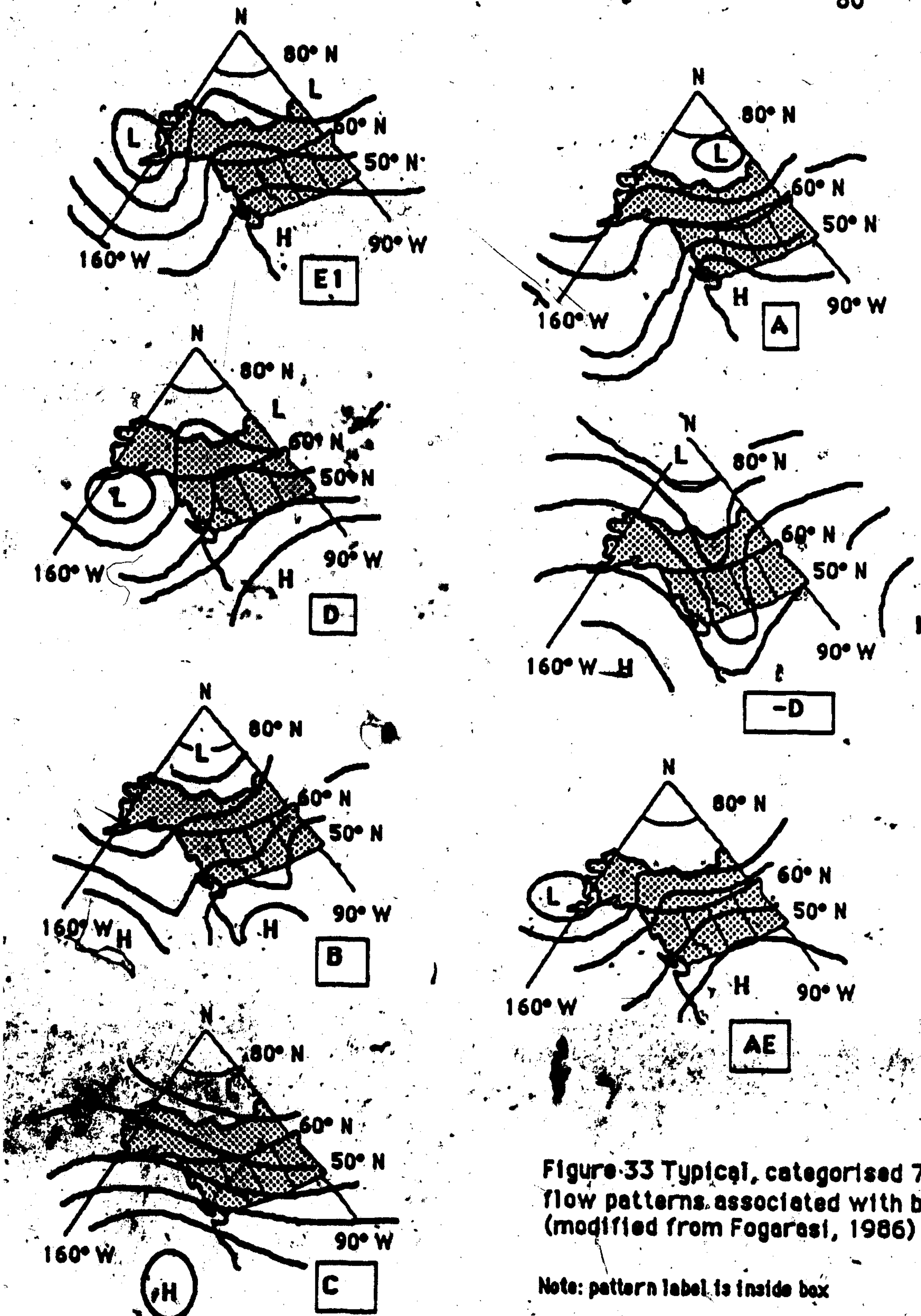


Figure 33 Typical, categorised 700-mb flow patterns associated with breakup (modified from Fogarasi, 1986)

Note: pattern label is inside box

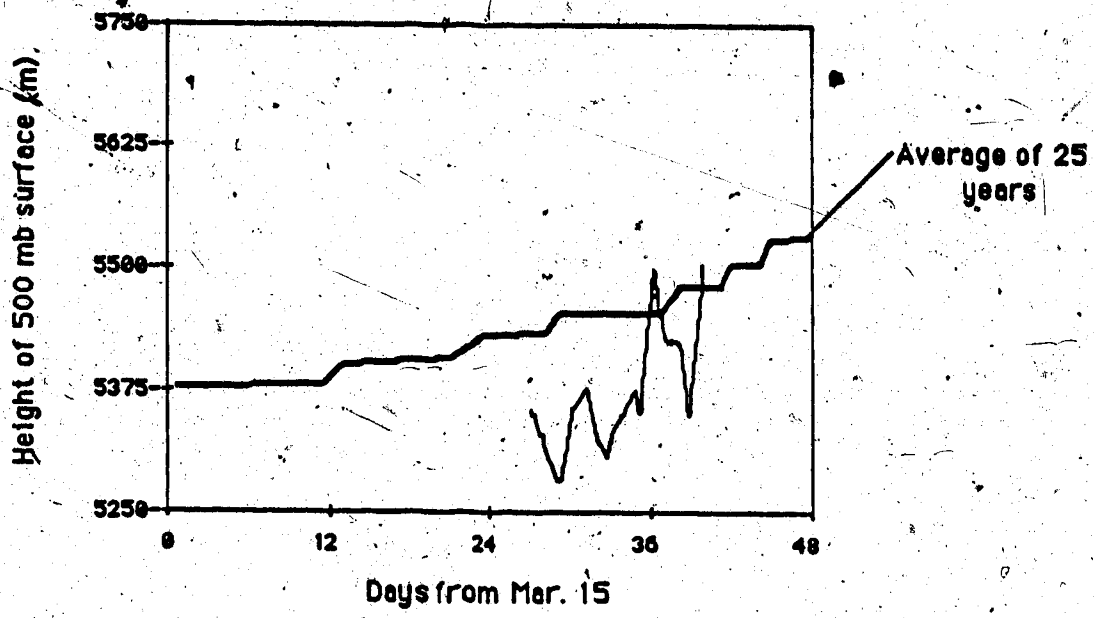
RELATION OF THE UPPER CIRCULATION TO BREAKUP AT FORT MCMURRAY

One problem with the use of 500 mb data is the relative scarcity of collection sites. The closest upper air station to Fort McMurray is Stoney Plain, Alberta, just west of Edmonton. Features of flow and heights are, however, usually of sufficient areal dimension at the 500 mb level to make the difference in characteristics for Fort McMurray not significant in a general qualitative analysis. A typical 500 mb feature, such as a wave, has a wave - length of 1000 to 10000 km and an amplitude of 2000 or more km (Holton, 1979). Therefore, for purposes of this investigation, it will be assumed that the large-scale features of flow will be identical for both Edmonton and Fort Mcmurray, hence generalizations concerning flow characteristics and heights will be considered to be equally applicable to Edmonton, Fort Mcmurray, and the intervening terrain.

500 mb Heights and Breakup Timing

An examination of daily 500 mb heights recorded at 1200 hours, GMT, for the period of increasing discharge on the Athabasca at Fort McMurray over 13 years of record indicates that heights in excess of those considered 'normal' - a positive height anomaly (PHA) - occurred annually, during the two weeks preceeding breakup. Figures 34 - 40 illustrate the trend of the 1200 GMT 500 mb height from 15 March to 30 April, for the years 1972-1984, inclusive. Table 12 contains relevant ridge data. On average, the last positive height anomaly of the 500 mb surface prior to breakup commenced 12 April, with a standard deviation of 8.5 days, ended 18 April, with a 6.6 day standard deviation, and persisted 6.5 days with an associated standard deviation of 4.2 days. Additionally, a PHA was the usual 500 mb condition at breakup - 9 of the years of record were in a PHA meteorological regime within 1 day of breakup, and no year of record escaped the influence of some form of upper ridge within a week of breakup. With, however, the standard deviation of the length of the PHA nearly as large as the mean PHA length, it is clear that the meteorological effect of ridge establishment may vary greatly from year to year.

Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1972



Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1973

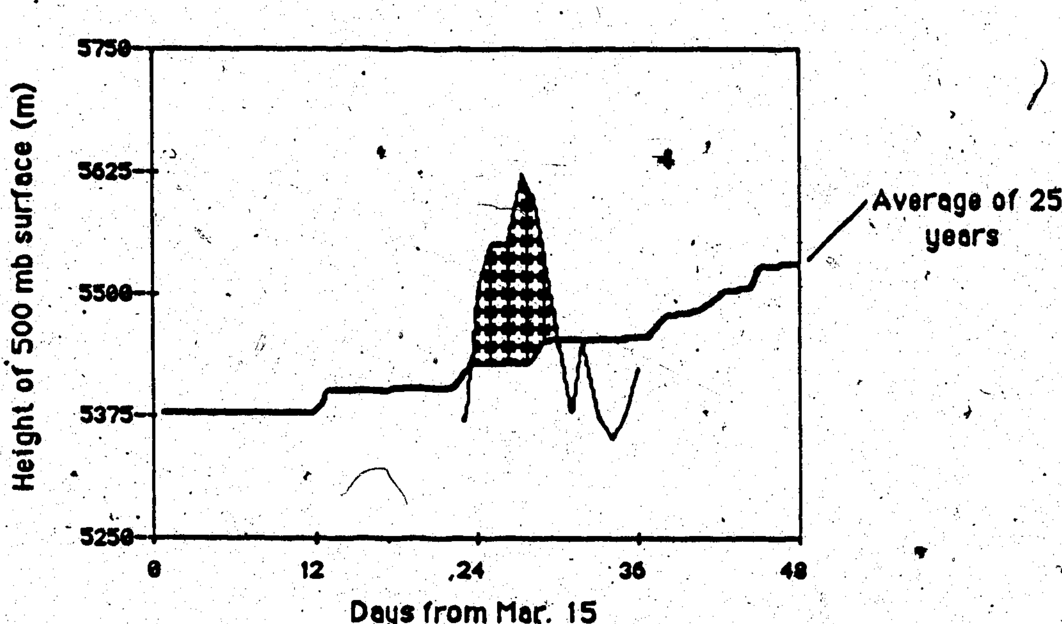
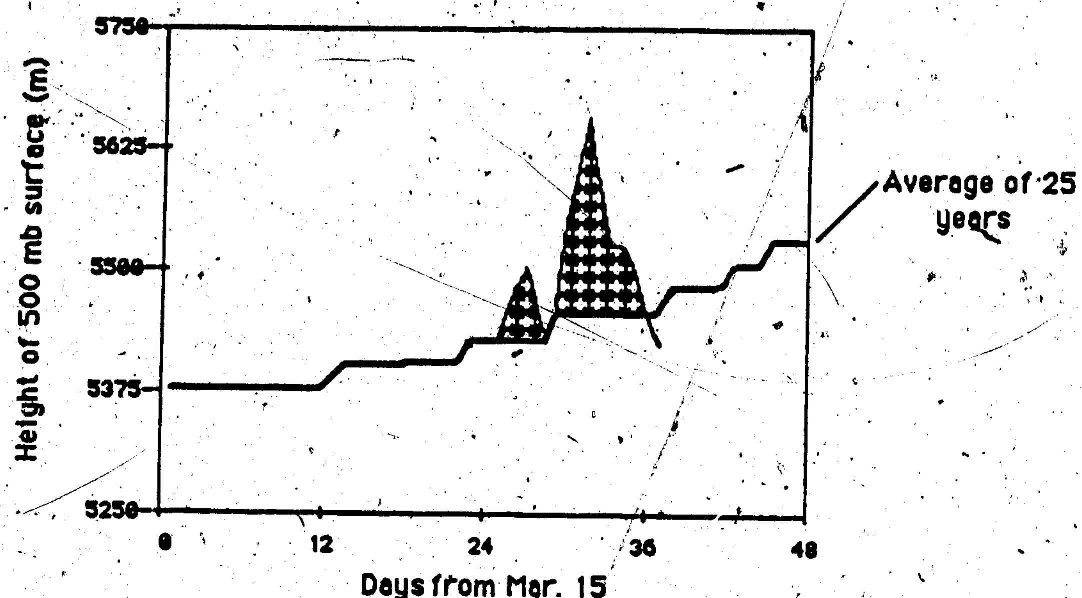


Figure 34 Height variation of 500 mb surface prior to breakup, 1972-73

Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1974



Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1975

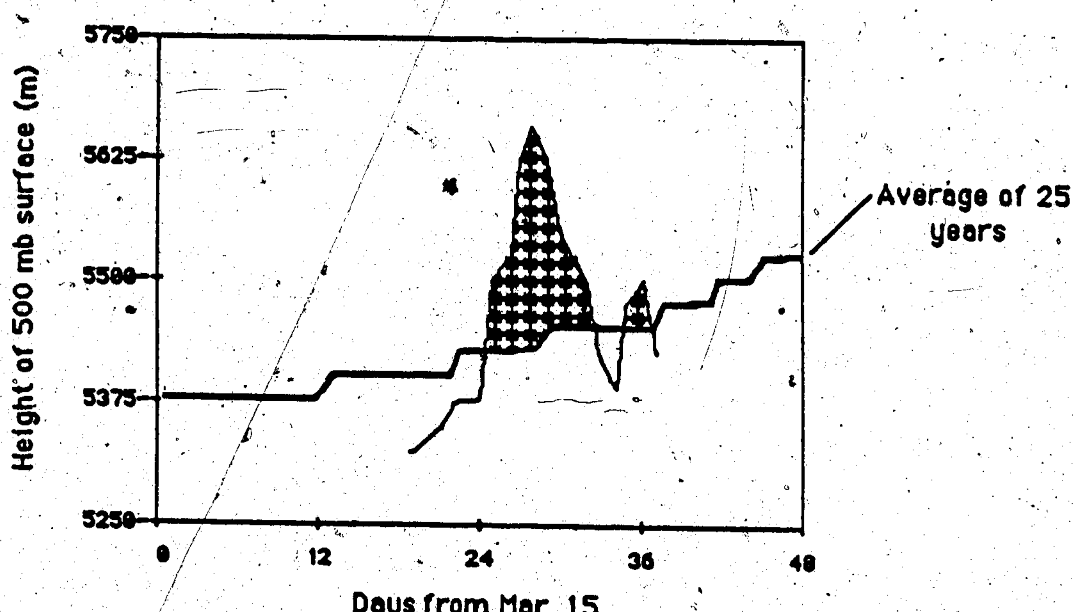
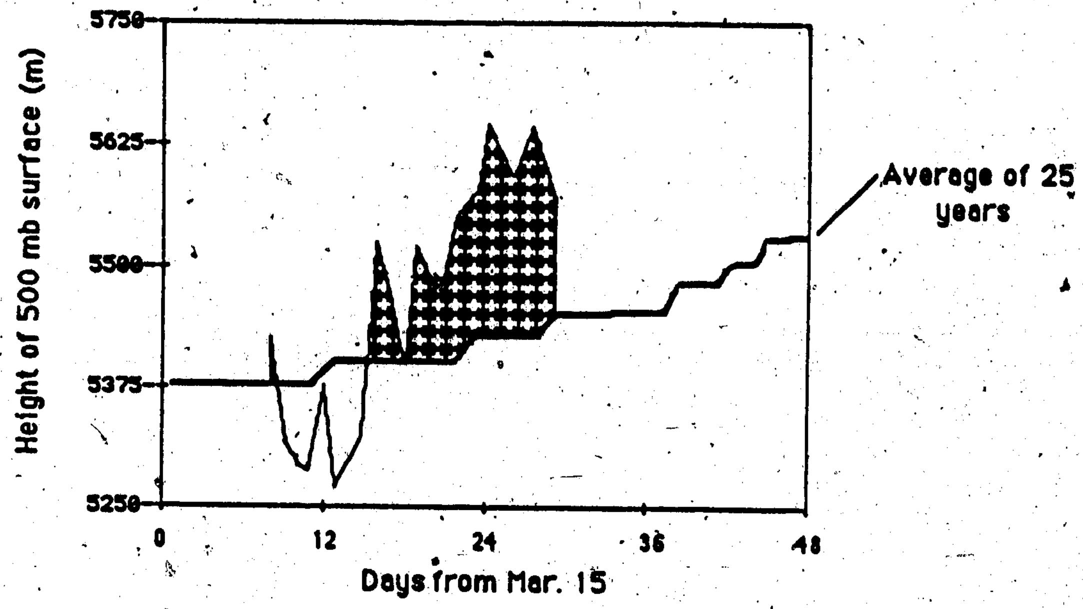


Figure 35 Height variation of 500 mb surface prior to breakup, 1974 - 75

Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1976



Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1977

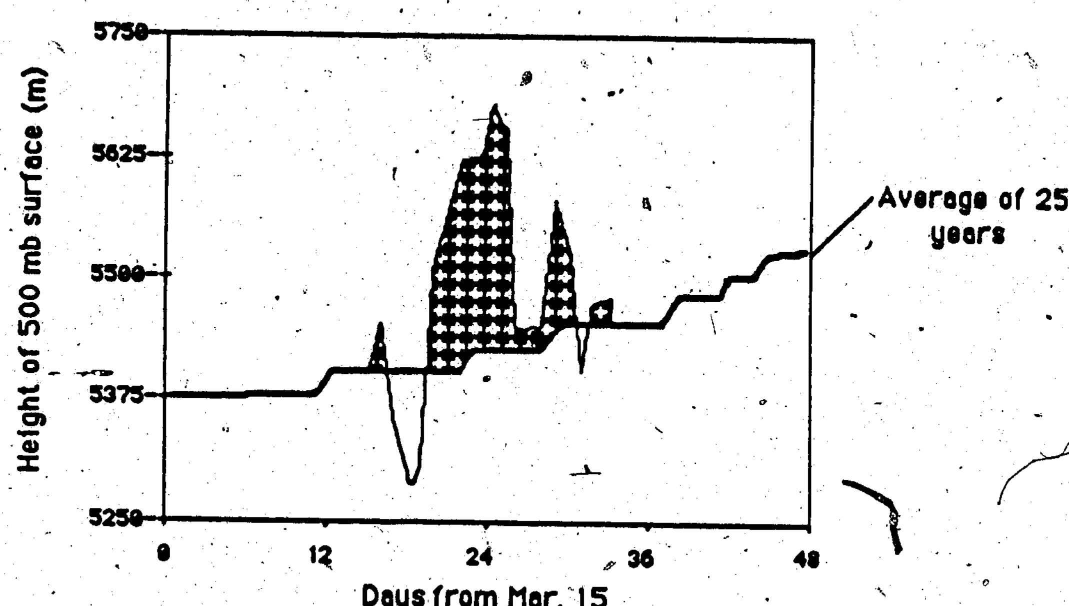
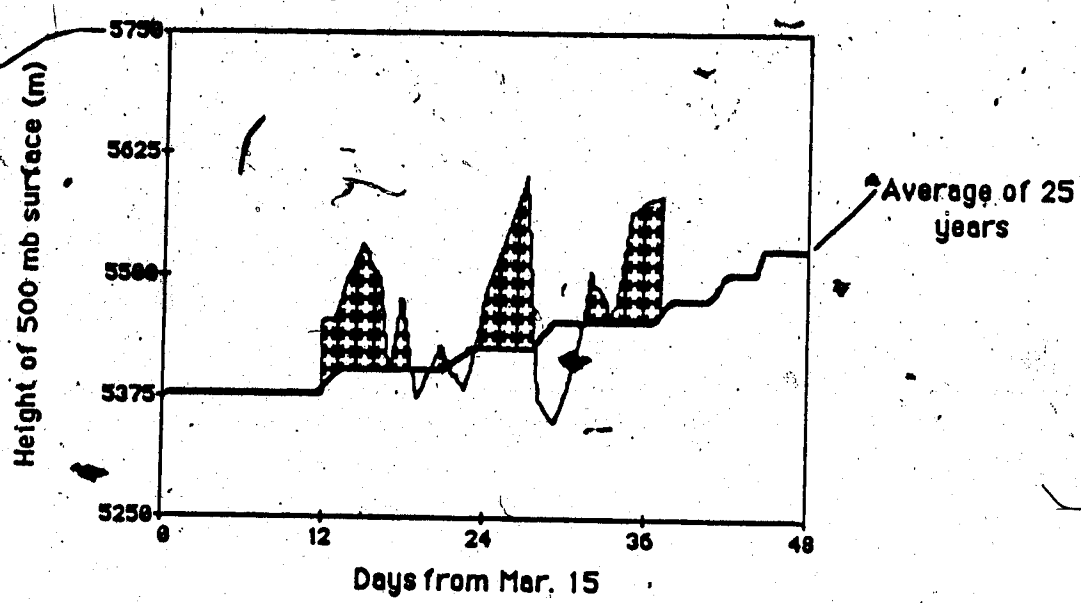


Figure 36 Height variation of 500 mb surface prior to breakup, 1976 - 77.

Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1978



Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1979

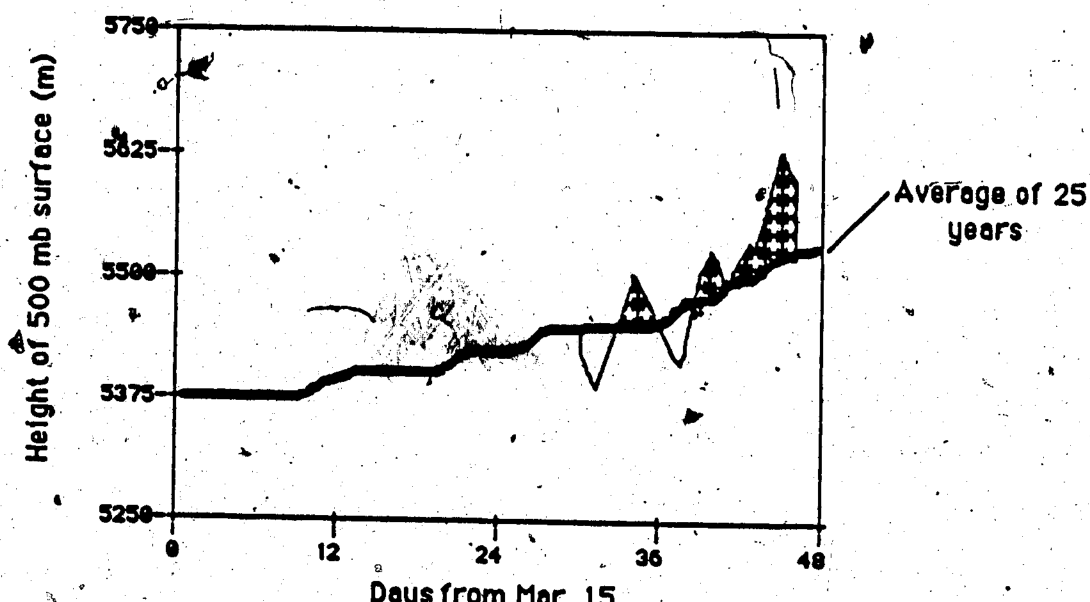
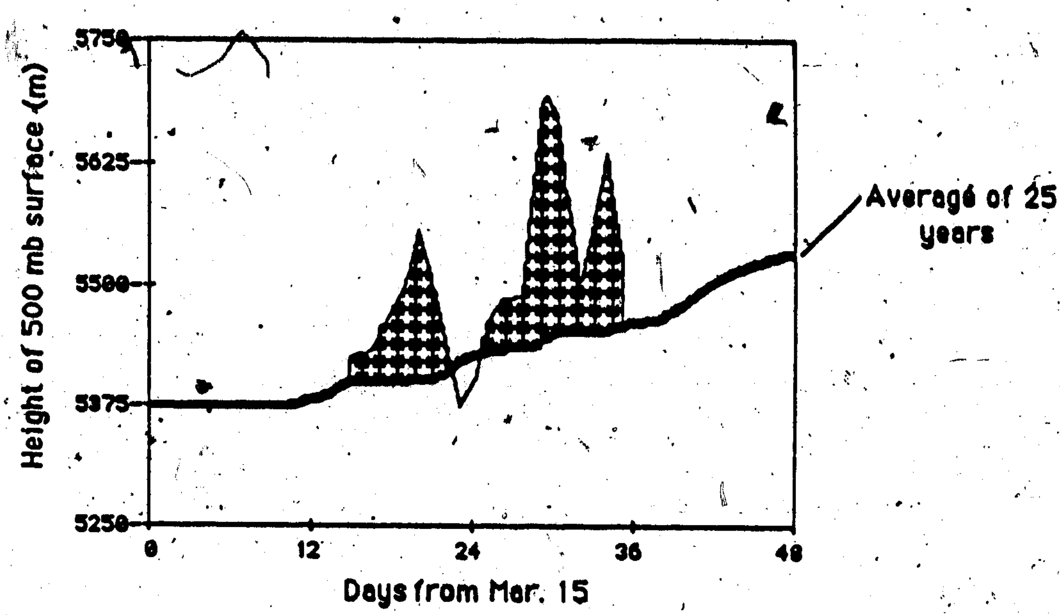


Figure 37 Height variation of 500 mb surface prior to breakup, 1978 - 79

Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup. 1980



Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup. 1981

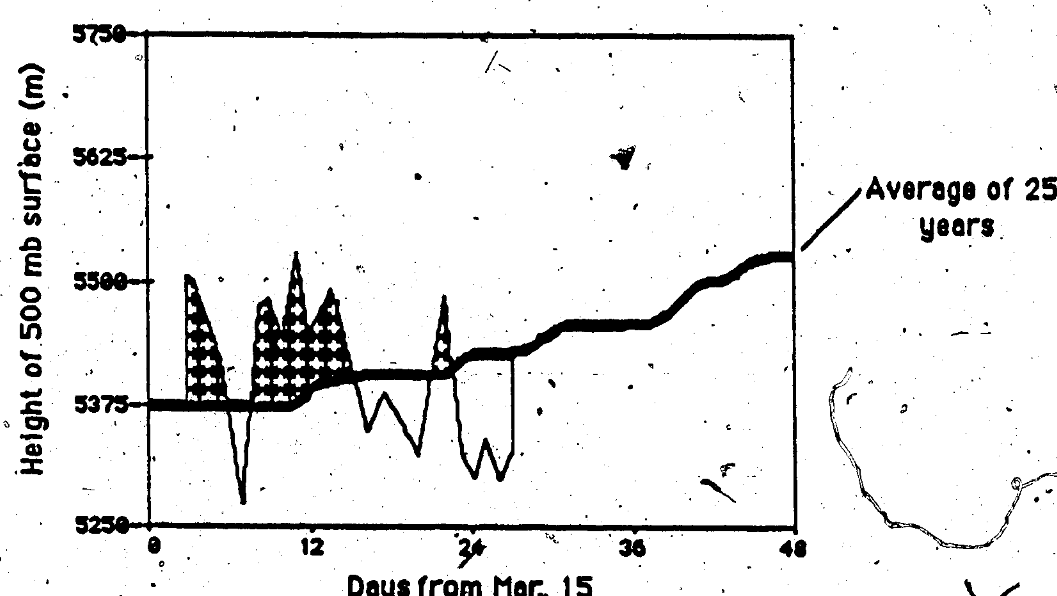
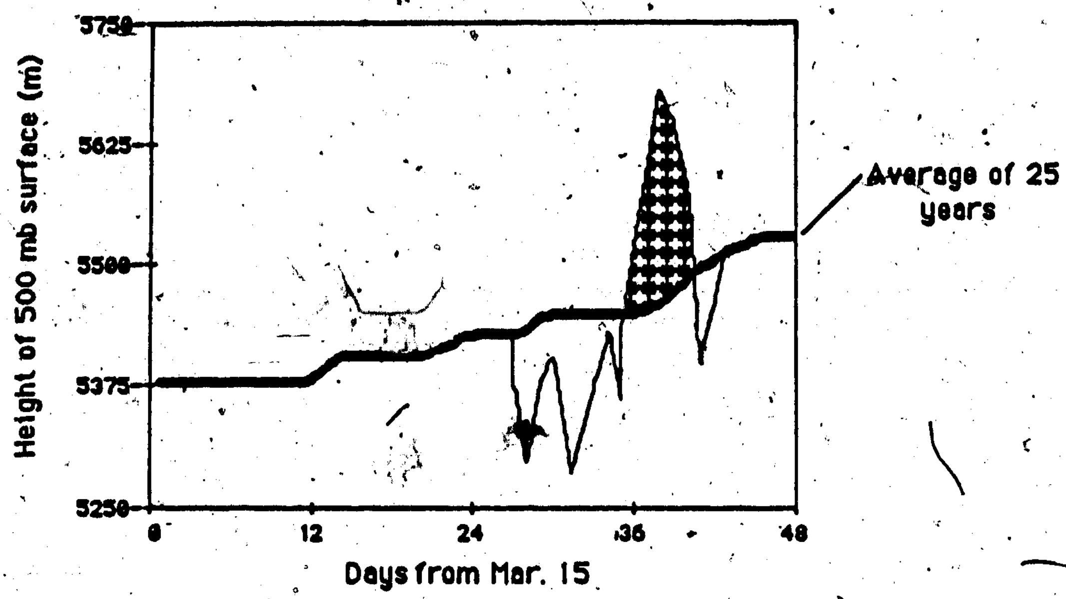


Figure 38 Height variation of 500 mb surface prior to breakup, 1980 - 81

Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1982



Height variation of 500 mb surface, from onset of increasing discharge, to day of breakup.1983

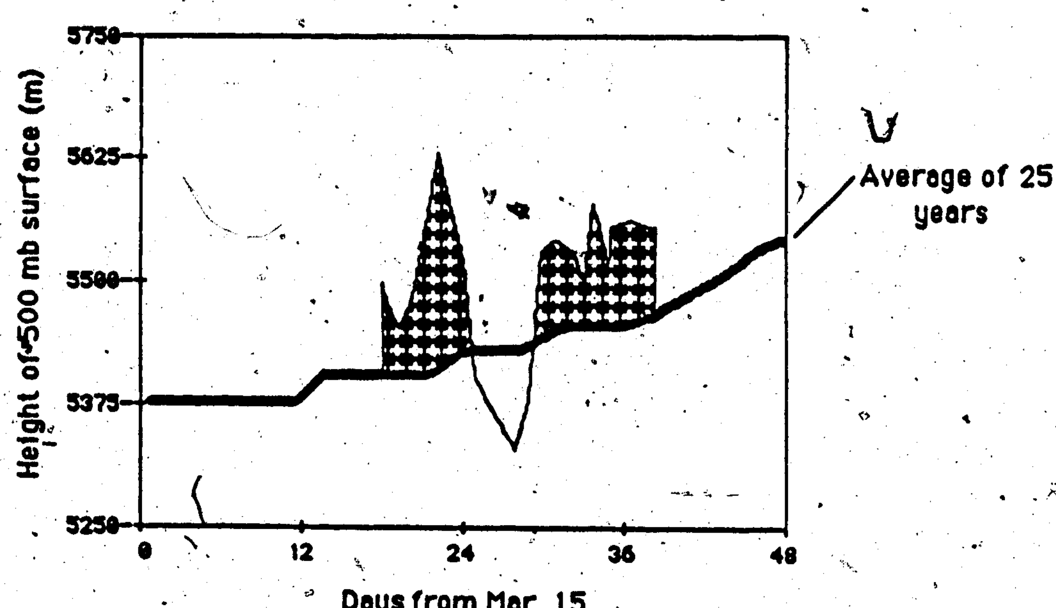


Figure 39 Height variation of 500 mb surface prior to breakup, 1982 - 83

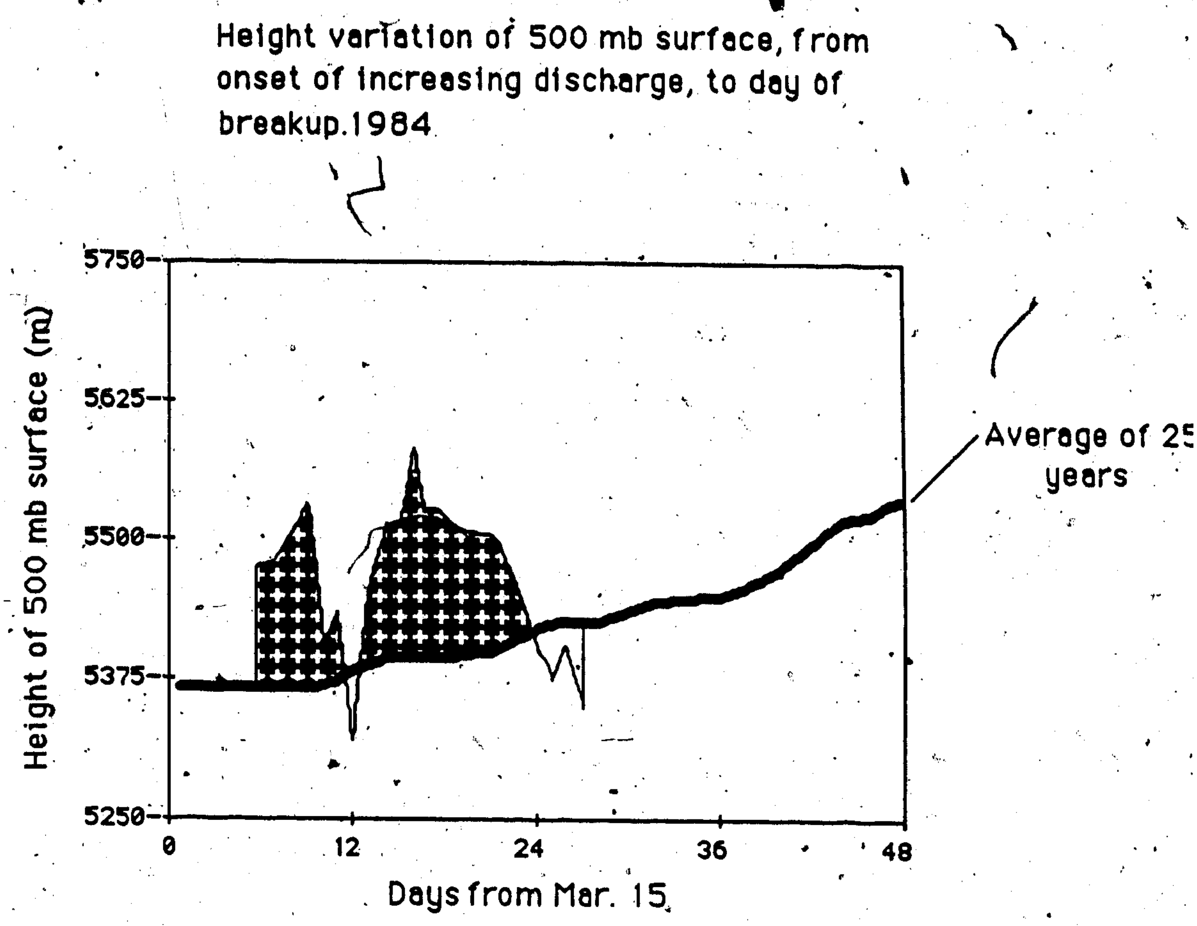


Figure 40 Height variation of 500 mb surface prior to breakup, 1984

Table 12 500 mb Positive height anomoly parameters during the pre-breakup period

Year	Start PHA	End PHA	Duration (days)	Mean height of PHA (m)
1984	March 27	April 7	11	93
1983	April 13	April 21	9	82
1982	April 20	April 23	4	157
1981	April 10	April 10	1	71
1980	April 8	April 18	11	128
1979	April 22	April 29	8	47
1978	April 13	April 18	6	70
1977	April 14	April 16	3	28
1976	March 30	April 12	14	135
1975	April 18	April 20	3	21
1974	April 13	April 18	6	111
1973	April 7	April 13	7	124
1972	April 23	April 23	1	34

Ridges, or at least a PHA, are phenomena that occur within days, and generally less than a week prior to breakup, during the years of record. This lends the forecast of ridge-building as a breakup precursor in early to mid April some credibility as a forecasting tool. It is their properties of intensity and persistence, however, that should show the greatest influence on the severity of breakup.

500 mb PHA and Breakup Severity

The lifespan, or 'persistence' of a PHA - labeled P_{500} for purposes of this analysis - in accordance with the usual meteorological definition, and without regard to its strength, may indicate a flow regime favourable to the development of a length of sufficiently enhanced warmth and radiation in a basin to accelerate the breakup process, including the decay of the river ice. If river ice decay is related to P_{500}, then the greater the persistence prior to breakup, the lesser the stage should be at breakup. Figure 41 illustrates the relation for the years of record. As expected, the relation of maximum stage at breakup to P_{500} is, although weak, an inverse one.

The intensity of a PHA - I_{500} - can be defined as the mean height in excess of the climatically normal height on a daily basis, termed H_{500}, divided by the persistence, or:

$$I_{500} = H_{500} / P_{500} \qquad (7)$$

High I_{500} values should indicate the presence of either a strong ridge or a strong impulse, with its usual meteorological effect, and low I_{500} values will tend to occur in more zonal conditions or low amplitude ridges.

A comparison of the maximum stage at breakup to I_{500} indicated the need for the insertion of some conditions regarding the timing of the PHA and the date of breakup. Firstly, an initial inspection of the I_{500} versus stage data reveals a wide variability in the stage response to similar intensities (Fig. 42). Some years experienced pre-breakup

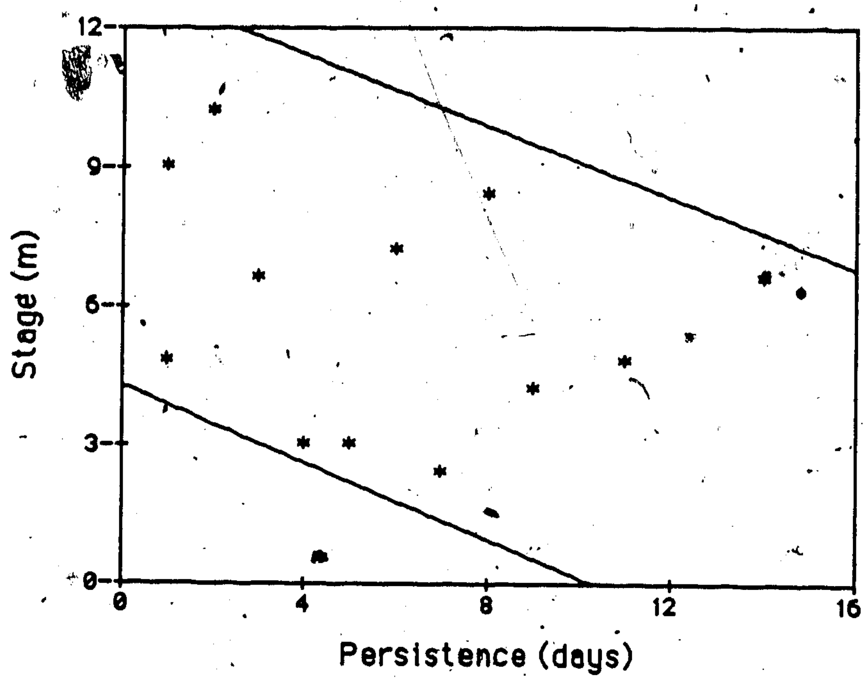


Figure 41 Maximum breakup stage versus ridge persistence

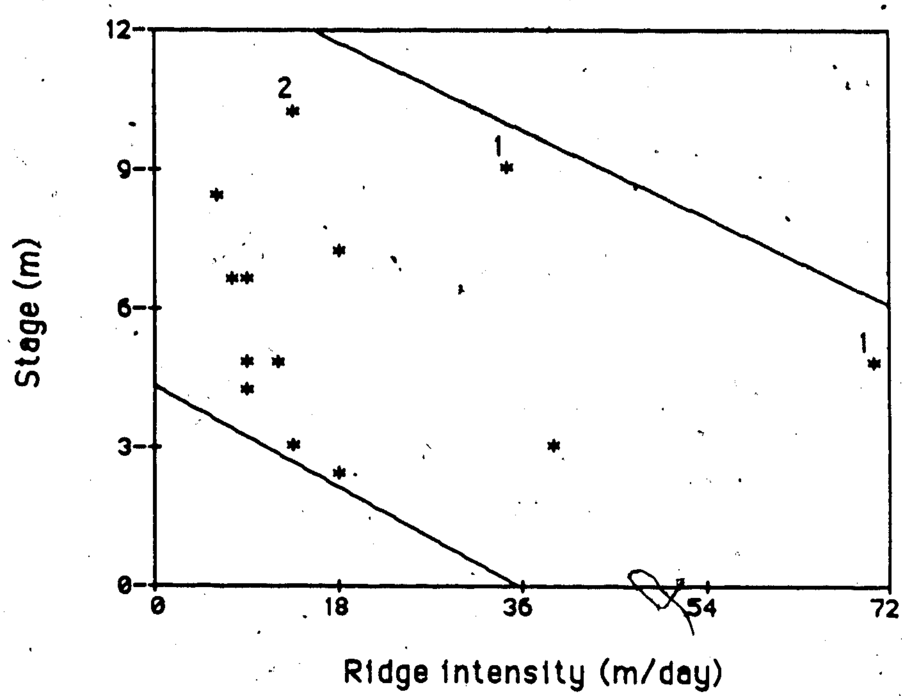


Figure 42 Maximum stage at breakup versus I500

Data points incorporating 2 or fewer days of persistence indicated

PHA of only one or two days duration, as indicated, and do not seem to fit the overall pattern of the other data. These short ridges may indicate the passage of transient, short -wave features, and hence not indicate a major adjustment to the upper flow. Based on the observed response of basin discharge to a four day period of measurement, it was supposed that a shorter period of persistence would not produce significant basin effects, and so it was decided to omit those years with PHA persistence of less than four days for the purpose of comparing stage to I_{500}.

The resulting relation has less scatter than one incorporating the shorter persistence years and has a correlation coefficient of approximately -0.5., hence it seems that I_{500} has a weak inverse relation to maximum stage at breakup. Too few years of record are left in the analysis to be conclusive.

In those years when the last PHA prior to breakup persists for less than 4 days, it is possible that higher stages at breakup are a likely outcome. Of those 4 years with 3 or fewer days of persistence, 2 were flood years. (1972 and 1977). This is not an unexpected result, as a year with a ridge of limited persistence is likely to be a year either with generally cool and somewhat cloudy pre-breakup weather, and hence a year with relatively strong ice present at breakup, or a year with considerable discharge produced during a strong pre-breakup ridge that decays in the few days before breakup. The former scenario is descriptive of the 1972 flood, where ridge-type circulation was never established during the period of increasing discharge, and up to the date of breakup. Conversely, the latter scenario is the most likely for the 1977 flood, where a strong and lengthy pre-breakup ridge resulted in a high discharge, but decayed during the four days prior to breakup. A return to cooler weather in the final four days may have resulted in some reconsolidation of the river ice, but was insufficiently cool to diminish the trend of increasing discharge.

Breakup forecasting method using 500 mb data

Both the properties of upper ridges and their influence on the nature of breakup cannot be explicitly determined by a simple analysis such as the above. Although the general meteorological effects of ridges are understood, their meso and micro-scale effects on energy-related parameters affecting breakup cannot be explained without further study. It is clear, however, that changes in the general circulation, regardless of their magnitude, are precursors of breakup, and that these changes have occurred within a week of breakup. One of the objectives of this study was to provide a means of forecasting breakup severity and timing. Some examples of the general circulation changes associated with breakup can be depicted on 500 mb charts, using a technique known as "map typing"(Kociuba, 1974) . Figures 43 through 45 provide a simplified illustration of the pre breakup upper-flow changes, as depicted by the path and orientation of the 5400 m, 500 mb surface height contour, for selected years. It is assumed that the flow aloft is basically geostrophic - that is, it is parallel to the contours. Figure 43 illustrates the large-scale shift in atmospheric circulation that occurred 2 weeks prior to breakup in 1975. A large upper low dominated the circulation over the western half of the continent in early April. A rapid north-western retrogression of the low, combined with the development of an upper high pressure feature in Saskatchewan allowed for the advection of warmer air into Alberta and increasing river flow commenced. A strong ridge with a considerable PHA was established by the middle of the month as the result of an eastward movement of a Pacific ridge. This feature persisted until 5 days before breakup, when conditions became slightly unsettled, but remained mostly clear. The long persistence of the ridge seems to agree with the relatively low breakup stage experienced that year.

Figure 44 indicates how only a slight shift in the upper flow can signal the beginning of the breakup sequence. A generally north-westerly flow aloft, in early April, 1974, veered to the southwest just prior to mid-month, and basin melt commenced. An initially strong but weakening ridge remained in place for 11 days thereafter, however it was too weak to prevent the return of the cA front to the vicinity of Fort McMurray, 3 days prior to breakup. It brought cloudy and cooler weather , and a resultant reconsolidation of the river ice may have been responsible for the subsequent severe breakup.

Figure 45 illustrates the flow regime in the 4 days prior to the date of breakup in 1977. An earlier 10 day period of a PHA had likely primed the river for breakup. From 4 - 2 days before breakup commenced, a short wave trough altered the upper flow, and cool and cloudy weather prevailed basin-wide, possibly giving river ice a chance to refreeze somewhat, and to reduce snowmelt, thus delaying breakup. Clearing and warmer

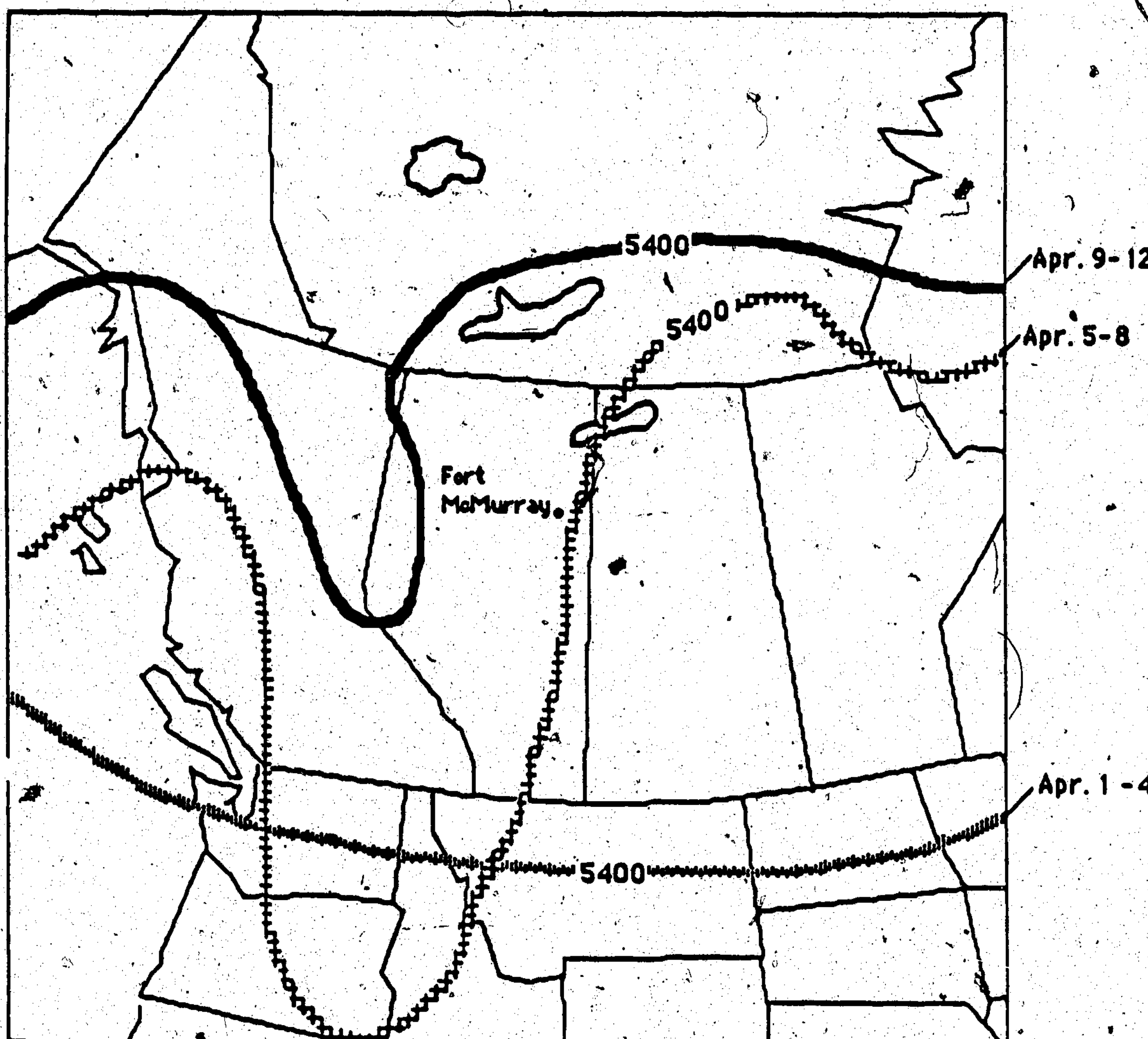


Figure 43 Movement of 4 day mean 500 mb height contours, April 1 - 12, 1975

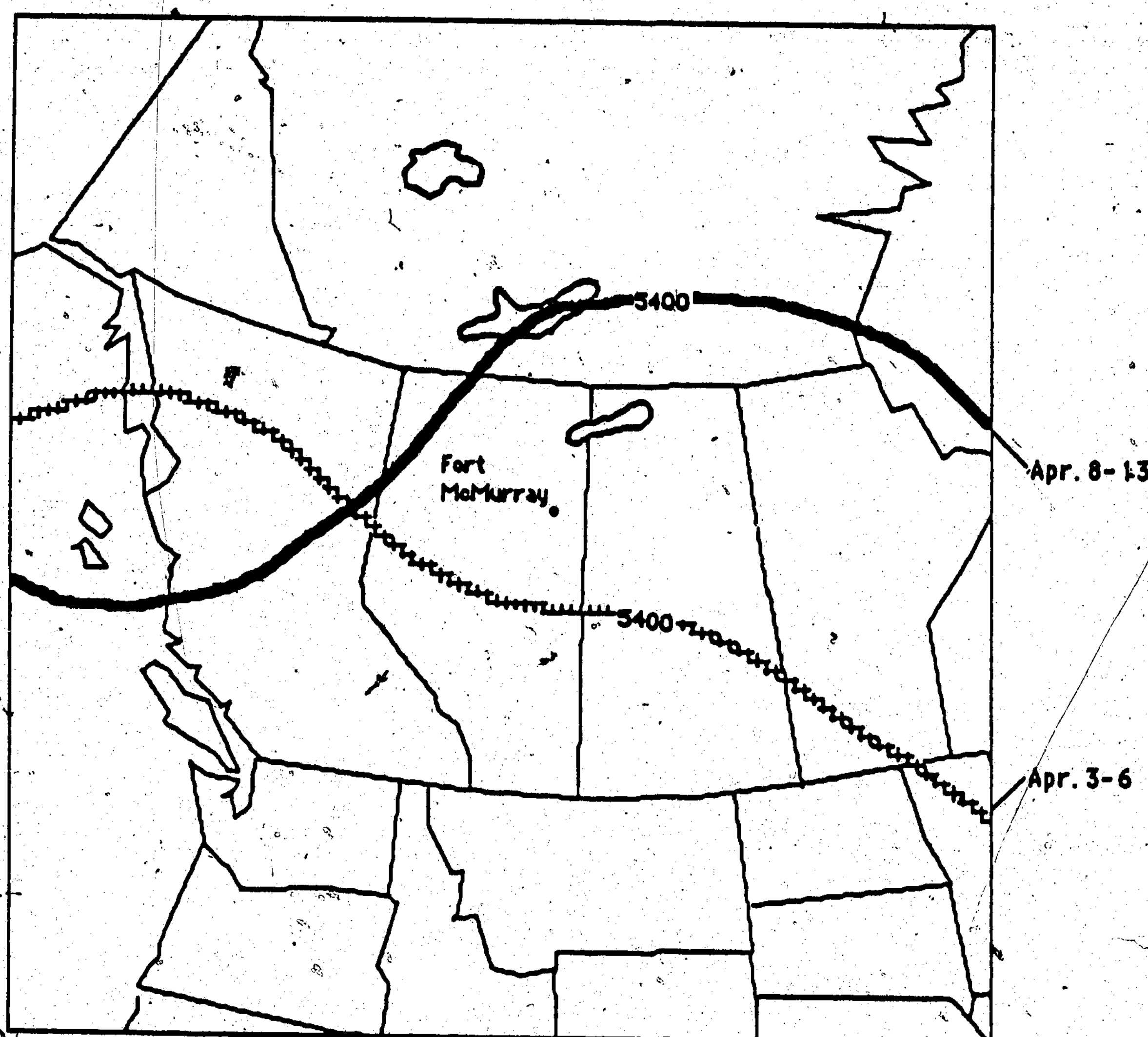


Figure 44 Movement of 4 and 7 day mean 500 mb height contours,

April 3 - 13, 1974

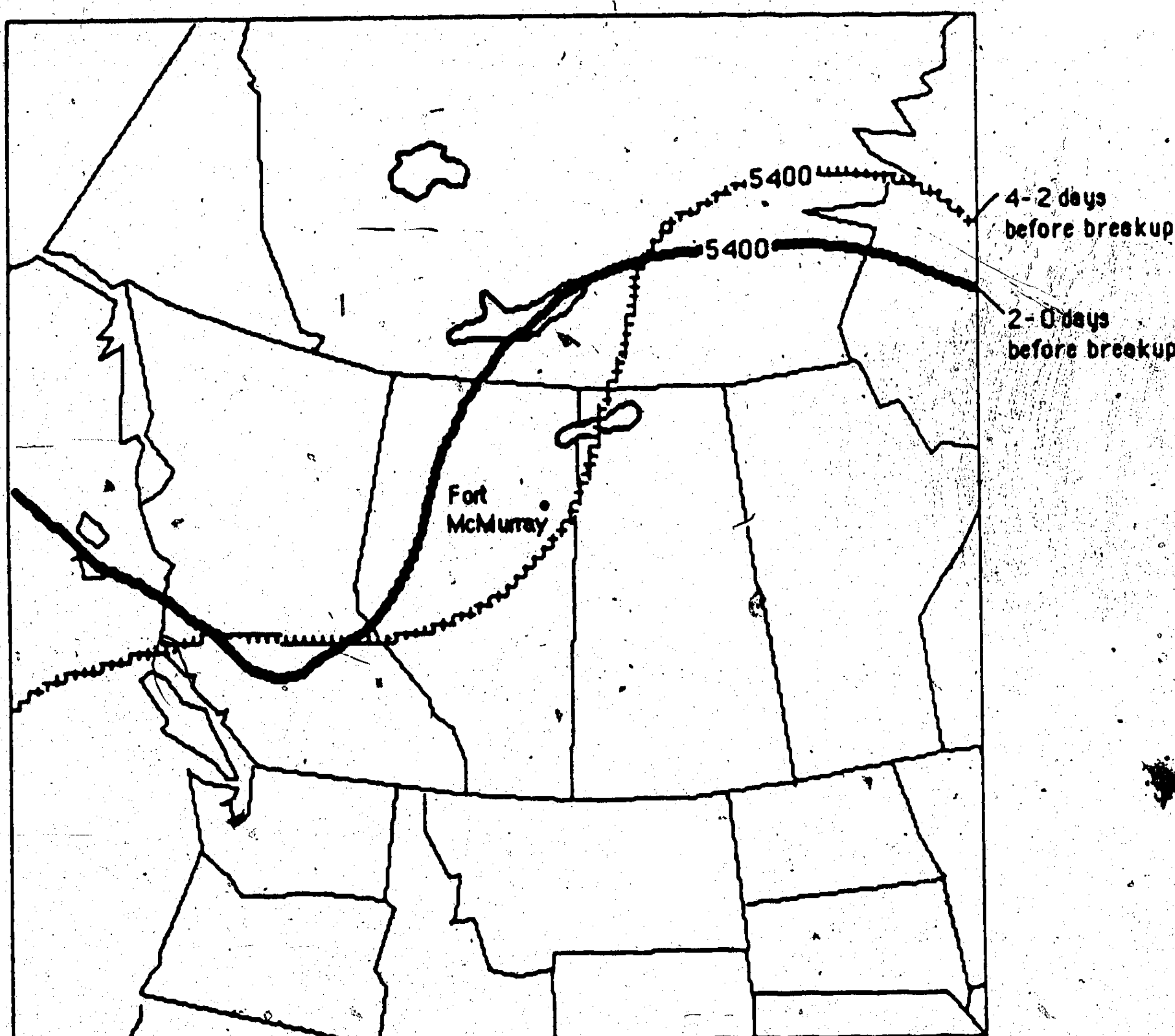


Figure 45: Movement of 2-day mean 500 mb. height contour, April 13-16, 1977

weather in the final two days may have precipitated the event, but the increased strength of the ice resulting from a period of cooler weather just prior to breakup could have contributed to the high stage that year.

A forecaster can examine upper charts, and upon the detection of analogous shifts in the upper flow occurring within roughly the same periods as the above three examples, should be aware of the enchanced possibility of breakup, or the possibility of a breakup with enhanced severity occurring shortly thereafter. The selection of charts is, however, not comprehensive. The upper flow patterns are too complex to categorise without the analysis of a larger database.

CHAPTER 6

CONCLUSION

The dynamic connection between meteorological variables and breakup is not well understood. An examination of the meteorological conditions associated with breakup has, however, inferred the existence of some promising links.

Firstly, an analysis of a few climatic variables has revealed two such links: degree days of thaw, and hours of bright sunshine, perform well in combination as an index of runoff for the lower section of the Athasbasca River. Perhaps these two variables have universal appicabilty to discharge forecasting in similar climatic regimes. Reliable discharge data are necessary when developing a forecast of breakup severity.

Secondly, three regression equations using the same meteorological variables, but of differing form have been developed to describe the maximum breakup stage. The non-linear equations represent an attempt to incorporate a reasonable assumption of the relative physical relationships of breakup parameters, and do so with some success. One in particular was chosen for stage forecast purposes on the basis of its slightly lower standard error of estimate.

A comprehensive energy balance method of forecasting run-off and ice deterioration may be more accurate than an empirical correlation of breakup conditions to degree days of thaw and bright sunshine. It would, however, be vastly more complicated. The empirical methods seem to have a satisfactory accuracy and have some utility as forecasting tools. A forecaster can, for example, by using the short term weather predictions publicly available, determine with reasonable confidence the maximum stage of breakup up to four days in advance.

An investigation of those hydrometeorological parameters hypothesised to be associated with the timing of breakup did not meet with any success, however. It seems there are short-period hydraulic effects in the flow that may initiate breakup, but do not lend themselves to description in a similar fashion to stage and discharge.

Finally, a cursory examination of the upper synoptic meteorological data has indicated that it is possible, through the examination of the trends in the upper flow at

500 mb in April, to determine the approximate time of breakup and to make a reasonable estimate of its severity. A shift in the upper flow is a breakup prerequisite, and such a shift indicates that breakup will occur within about two weeks. An examination of the nature of the shift in flow, including the establisment of a ridge, its persistence and its intensity may infer breakup severity. Long-wave changes in the upper flow are breakup prerequisites, but it is the short wave variability in the few days before breakup that seems to control the severity of the event. The synoptic aspects of breakup are the least well understood, but may have the most potential to become the universal means of describing breakup characteristics.

A more extensive data base will endow future studies of breakup with greater statistical confidence. Moreover, a basin - wide consideration of climatological factors may reveal some peculiarities of certain basin sections and reveal their affect upon the breakup sequence. The upper atmospheric synoptic aspects of breakup are under-investigated and show great promise. An extensive map-typing technique, much greater than that attempted in the last section of this thesis, may reveal that a limited number of characteristic flows will serve, in a general manner, to describe breakup, or to reveal its potential for severity.

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Appendix A

U. S. Corps of Engineers Snowmelt Model (From Storr, 1978)

This version of the U.S. Corps of Engineers snowmelt model was developed in 1960, and is:

$$M = k' (1 - F) (0.004KY) (1 - a) + 0.0084kV (0.22 T'_a + 0.78 T'_d) + 0.007 RT'_a$$

where M is total melt in inches per day, and the four right hand terms include melting from shortwave and longwave radiation, convection and condensation, and melt due to rain on snow events.

The individual terms are:

k' - short wave radiation melt factor on an average slope and aspect as compared to an unshielded horizontal surface (m /W^2)

F - the average fractional forest canopy coverage

KY – the symbol for incoming shortwave radiation (W/m^2)

a - the average snowcover albedo

T'_a - the difference in degrees Farenheit between the temperature at the surface and 10 feet aloft

k - a convection/condensation factor dependent on wind

V - the mean wind speed at 50 feet aloft in MPH

T'_d - the difference in degrees Farenheit between the dewpoint at 10 feet aloft and the surface

R - the rainfall in inches

Appendix B

The Campbell - Stokes sunshine recorder (from Canadian Climate Normals, Atmospheric Environment Service).

In Canada, bright sunshine observations are made by the Campbell - Stokes sunshine recorder, first developed in 1863. Sunshine is recorded by the use of the magnifying glass paper burning technique.

The recorder consists of a 10 cm in diameter glass sphere, mounted in the centre of a spherical bowl. The sphere foccuses the suns rays onto a card placed in a pre-ordained position within the bowl, and the rays burn or scorch a trace onto the card.

The cards dimension vary with the season: equinox, summer or winter solstace, and are incremented in intervals of 1/10 hours of exposure. Observations of bright sunshine are accumulated at individual stations and forwarded monthly to AES for checking and processing.

Appendix C

Fisher Z Transformation

When a corellation coefficient (r) is calculated on the basis of a sample of data, the resulting value of the coefficient is only an estimate of the population corellation coefficient, denoted by ρ.

To make inferences of ρ from r, several assumptions must be made concerning the distribution of the observed variables. One important assumption is that the values of the x's are random variables with a normal distribution. According to Freund (1984), the sampling distribution of r is compicated under these assumptions, hence inferences of ρ are based on the Fisher Z tranformation, a transform of r to Z, where Z is given by:

$$Z = 1/2 * \ln((1+r)/(1-r))$$

R.A. Fisher was able to show that, for any value of ρ and given the previous assumption, the distribution of Z is normal with:

$$\mu_Z = 1/2 * \ln((1+\rho)/(1-\rho))$$

and

$$\sigma_Z = 1/(n-3)^{1/2}$$

hence

$$z = (Z - \mu_Z)/\sigma_Z = (Z - \mu_Z) * (n-3)^{1/2}$$

is the standard unit.. To construct confidence intervals for ρ, confidence intervals are constructed for the mean of z, by substituting

$$z = (Z - \mu_z) * (n - 3)^{1/2}$$

for the middle term of the double inequality given by:

$$-z_{\alpha/2} < z < z_{\alpha/2}$$

and then algebraically manipulating the terms until the middle term is μ_z.

This leads to the following (1 - α) 100 % confidence interval for μ_z:

$$Z - z_{\alpha/2} / (n - 3)^{1/2} < \mu_z < Z + z_{\alpha/2} / (n - 3)^{1/2}$$

Using standard statistical tables, we can convert this μ_z value to a confidence interval for ρ, based on a measurement of r.

Appendix D

The Mann - Whitney U test (from Freund, 1982)

This is a test designed to test for the difference between two means. It determines if 2 samples come from identical populations, without the requirement that the sampled populations are normally distributed.

The U test is commenced by arranging the data jointly by rank, say, from largest to smallest. Next, if the sample sizes are n1 and n2, the sum of the ranks of each sample W1 and W2 is:

$$(n1+n2) * (n1 + n2 + 1) / 2$$

Now $U1 = n1*n2 + n1 * (n1 + 1) / 2 - W1$

and $U2 = n1*n2 + n2 * (n2 + 1) / 2 - W2$

The statistic U is always the smaller of U1 and U2. If U is less than or equal to a critical value found in tables, then the mean of sample 1 does not equal the mean of sample 2, and thus they are drawn from different populations.