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COASTAL IMPACTS OF CLIMATE CHANGE: BEAUFORT SEA EROSION STUDY

S.M. Solomon, D.L. Forbes, and Brian Kierstead

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PREAMBLE

Human activities are altering the composition of the atmosphere, thereby altering the atmospheric 'greenhouse' effect. An increase of radiatively active gases in the atmosphere is expected to result in overall warming of our planet. Compositional change has already occurred but its effects cannot yet be rigorously identified because of our limited understanding and the complex functioning of the climate system. Because of the compositional change, the Intergovernmental Panel on Climate Change[1] considers a one-to-four degree Celsius warming of the mean temperature of the global atmosphere likely to occur over the next 30 to 50 years. Within the Arctic, the warming is expected to be two to three times the global average. Its effects would be marked because of the sensitivity of snow and ice to increased temperature.

This report looks at coastal impacts of climate change in the Beaufort Sea coastal zone. It is a follow-on to the study by McGillivary et al (1993) which considered the effects of climate warming on the offshore ice and wave climate, with implications for the offshore oil and gas industry in the Canadian Sector of the Beaufort Sea as well as coastal communities.

The Mackenzie Delta and Beaufort Sea coastal zone is particularly sensitive to coastal erosion because it is low-lying and is composed of ice-rich, unconsolidated sediments. As a result, sea level rise and increased wave energy due to larger open water fetch, can be expected to increase coastal erosion rates.

In this report, existing air photographs are analyzed at four representative sites in the Beaufort Sea coastal zone to estimate rates of cliff recession over the past 30 to 40 years. Statistical data on relevant climatic and oceanographic variables are then analyzed to obtain a statistical relation between recession rates and climatic variability. These relationships are then used to project changes in coastal recession rates due to increases in wave energy caused by increased open-water fetch expected under a warmer climate.

STUDY HIGHLIGHTS

This study has found that:

- Within the Beaufort Sea coastal zone, observed coastal recession rates varied spatially and from year to year by over an order of magnitude. The average annual volumetric land loss for the 1947 to 1986 period along the Tuktoyaktuk town site shore was 4000 m^3a^{-1}. For the other three sites, the rates were 4800 m^3a^{-1} for North Head, 9000 m^3a^{-1} for Tent Island, 17400 m^3a^{-1} for Kay Point.

- Using observed storms defined on the basis of wind speed greater than 37 km/hr and

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[1] A panel reporting to the World Meteorological Organization and to the United Nations Environment Programme.

duration greater than 6 hours, a storm intensity index has been developed incorporating ice-free fetch deepwater significant wave height and storm duration.

- Using this storm intensity index, coastal sites at Tuktoyaktuk, North Head, and Tent Island were found to have experienced strong variations in storm intensity over the past 33 years, with greater storminess in the early to mid-1960s and in the 1980s and a quiet interval from the late 1960s through the 1970s. Kay Point, on the central Yukon coast and closer to the summer ice edge, displayed less variation in storm intensity.

- A strong correlation was demonstrated between this storm intensity index and coastal erosion rates at Tuktoyaktuk and Kay Point. Other factors such as ice scour, ice entrainment of sediment, thermal degradation and thaw consolidation are apparently less important.

- The study indicates that typical cliff recession rates will accelerate to levels which are as high as the maximum historical rates due to changes in wave climate caused by increased extent and duration of open water suggested by McGillivary et al. 1993.

- A common practice in areas of coastal erosion hazard is to plan setback of new construction based on current erosion rates so as to ensure a reasonable life expectancy of new structures. Due to accelerated coastal erosion rates, procedures for determining appropriate setbacks should be revised for structures with life expectahcy of 50 years or more.

- Present relative sea level rise is thought to be at or less than 3 mm per annnum. Expected changes in sea level rise may more than double this rate and will reinforce wave climate changes indicated above.

INTRODUCTION

This report presents the results of an investigation of coastal erosion in the Canadian Beaufort Sea. It is an extension of work begun under the Northern Oil and Gas Action Plan and continued under the Green Plan project entitled Coastal Impacts of Climate Change. Funds for this study have been provided by the Panel on Energy Research and Development.

According to the Canada Oil and Gas Lands Administration, the Beaufort Sea and Mackenzie Delta area have proven reserves of 241 million m^3 of oil and 357 billion m^3 of natural gas, and potential recoverable reserves are estimated to be 1112 million m^3 of oil and 1918 billion m^3 of natural gas. Any decision to develop the reserves would represent a major capital investment. It would involveconstruction of facilities with an expected life of 30 to 50 years or longer. This is within the expected time frame of major environmental changes due to climate warming. There is a need to re-examine present approaches to engineering design since these assume a stable, though variable, climate.

This exploratory study examines how a warmer climate could effect changes in coastal erosion rates. Our approach is:

(a) to estimate current erosion rates using historical air photography; to develop empirical relation between these rates and environmental factors, especially wave energy and duration;

(b) based on the empirical results and on projected changes in sea ice cover and wave climate in the area, to predict changes in coastal erosion rates under a warmer climate.

The issue of the transition to a warmer, future climate is not addressed because it awaits better understanding of the climate system, e.g. using coupled models that introduce the effects and response of the oceans such as alteration of currents and changes in sea-ice extent and thickness. Figure 1 (modified from McGillivary et al., 1993) illustrates conceptually the way in which global climate change would impact the petroleum industry. Climate-system feedbacks are not shown but are implicit in the scenarios.

OBJECTIVES

The primary objective of the investigation is to relate environmental variables to coastal retreat rates in order to identify the response of the coast to climatic variability. Databases have been compiled on coastal retreat rates, erosion volume, storm occurrence, ice distribution and open-water fetch, melting degree days, water levels, Mackenzie River discharge, and coastal characteristics such as stratigraphy, ice content, seabed slope, and coastal orientation.

The analyses suggest that the rates of cliff retreat at Kay Point (Yukon coast) and at Tuktoyaktuk (prior to the installation of shore protection in 1987) are related to storm frequency and wave energy during the open-water season. It is therefore clear that coastal stability is sensitive to changes in open-water fetch and duration. As part of this study, we have also examined coastal retreat rates at North Head (Richards Island) and at Tent Island (Mackenzie Delta). However, the aerial photography and ground measurements are too sparse to enable a comparable analysis of coastal response at these sites.

REGIONAL SETTING

Coastal geology and geomorphology

The coastline of the Canadian Beaufort Sea (Fig. 2) is composed of unconsolidated but ice-bonded sediments, including mud, sand, gravel, and glacial diamict (Rampton, 1982, 1988). The ice content of these sediments can be considerable, with thick lenses of massive ice common at contacts between underlying porous sands and overlying impermeable diamicts (Rampton and Mackay, 1971).

Coastal landforms include low-angle tundra slopes gradually being drowned by the encroaching sea, deltas, tidal flats, supratidal marshes, beaches and barriers, lagoons, and complex embayments formed by breaching of thermokarst lake basins (Forbes and Lewis, 1984; Forbes and Frobel, 1985; Ruz et al., 1992; Solomon and Forbes, 1993). Cliffs are the dominant coastal landform, representing 52% of the shoreline (Harper et al., 1985). They are particularly common along the Yukon coast, on islands north of the Mackenzie Delta (including Richards Island), locally along the coast of the Tuktoyaktuk Peninsula, and in Liverpool Bay to the south and east (Fig. 2). Cliff morphology ranges from temporarily stable vegetated slopes to nearly vertical wave-washed cliffs, rising in some places to more than 50 m (McDonald and Lewis, 1973), although cliff heights of less than 10 m are more common. Cliff erosion processes include gullying, basal wave cut, shallow sloughing, block failures, and retrogressive thaw failures. Retrogressive failures occur where massive ice is exposed in retreating headwalls. They develop amphitheatre basins with associated mudflows that transport sediment downslope from the headwall source to the shore. These features are concentrated along the Yukon coast, on parts of Richards Island, and in the vicinity of Tuktoyaktuk (Fig. 2; see Harper et al. 1985). They show a tendency for cyclical development, with stabilization and reactivation on time scales of the order of 10 years (Forbes and Frobel, 1985).

The other dominant feature of the Canadian Beaufort Sea coast is the Mackenzie Delta, the largest in Canada, second largest in North America (after the Mississippi), and second largest in the Arctic Ocean (after the Lena). It has a delta plain occupying almost 13,000 km^2 and a subaqueous platform covering 6930 km^2 out to the 12 m isobath (Lewis, 1989). With a mean annual discharge of almost 10,000 m^3s^{-1} of relatively warm water, the Mackenzie River exerts a profound influence on the oceanography and ice cover in the delta region, with implications for coastal stability. Despite contributions of the order of 10^9 metric tonnes of suspended silt and clay and lesser quantities of sand, representing some 95% of all sediment supplied to the Canadian Beaufort Sea, large parts of the delta front are eroding at typical rates of the order of 2 m a^{-1}, but locally more than 10 times that rate (Harper et al., 1985). However, wide mudflats along the west side of Richards Island and aggrading channel-mouth bars in other areas attest to local progradation (Forbes and Frobel, 1985; Jenner and Hill, 1989).

Sea ice and coastal oceanography

The coastal areas of the Beaufort Sea are ice covered for 8 to 9 months of the year. Freeze-up begins typically in October and break-up in June. The ice is often frozen to the seabed in water depths less than 2 m. Floating landfast ice extends offshore to a shear zone at the edge of the mobile polar pack. Pressure ridges, which develop in the shear zone, cause widespread scouring of the seabed in water depths greater than 8 m. The landfast ice zone is most extensive in the Mackenzie Delta region but quite narrow west of Herschel Island and east of Cape Dalhousie.

During the open water season, ice-free fetches of more than 100 km are common. Storm winds, which become increasingly frequent in late August and September, come predominantly out of the west and northwest, with a secondary mode from the east. Winds blowing over open coastal waters generate significant wave heights of 4 m or more with peak periods up to 10 s (Pinchin et al., 1985). The 100 year storm design wave is 6.2 m (Eid and Cardone, 1992)

The range of astronomical spring tides is no more than 0.5 m, but winds can generate positive and negative storm surges (Henry, 1975). The maximum storm surge limit in the Tuktoyaktuk area is about 2.5 m above mean water level (Forbes and Frobel, 1985; Harper et al., 1988). Water level changes during surges occur over a few hours and can generate significant currents (>0.5 m s^{-1}) within restricted embayments (Solomon and Forbes, 1993). Higher water levels during storms also allow larger waves to reach the shore and increase the limit of wave runup.

Regional distribution of coastal recession

Published data on coastal recession is presented in Figure 3, normalized to volumetric erosion (m^3a^{-1}) per metre of shoreline. The data are computed as the product of cliff height and rate of retreat. While some of the rapid rates of shoreline retreat are measured along the Mackenzie Delta front (e.g. about 10 m a^{-1} at Tent Island), the volume loss is limited by the low height of the shore scarp (typically about 1.5 m). Our data indicate volumetric erosion rates between 7 and 19 m^3a^{-1} for delta-front sites. In contrast, the rates of cliff retreat measured at Hooper Island generally range from 0.9 to 4.2 m a^{-1} (Forbes and Frobel, 1985; Gillie, 1987; Hill and Frobel, 1991). With cliffs up to 30 m in height, these retreat rates correspond to volumetric losses of 27 to 126 m^3a^{-1}, up to seven times the maximum recorded along the delta front. It should be noted that these comparisons do not take into account the relative proportions of ice and sediment in the eroding cliff faces, a factor that is critical to any sediment budget analysis.

The exposed outer coast of Richards Island exhibits the highest rates of volumetric erosion. Rates along the Yukon coast and in the modern delta are lower. The Tuktoyaktuk Peninsula is eroding at intermediate rates. This is partly a function of the amount of wave energy reaching the various parts of the coast, as described in more detail later in this report. Wave energy along the Yukon coast is restricted by the proximity of pack ice during much of the open-water season. Waves are highly attenuated along the modern delta front by extensive areas of shallow water and a soft muddy seabed. Wave energy along the exposed outer Richards Island and Tuktoyaktuk Peninsula coasts is somewhat higher. The differences in recession rates between the latter two areas may be partly a function of cliff compostion.

APPOACH AND METHODS

The approach taken in this study is as follows:

(1) to identify the major variables affecting the rate of coastal retreat in the Canadian Beaufort Sea,

(2) to compile statistical information on the relevant climatic and oceanographic variables,

(3) to investigate methods of measuring coastal retreat,
(4) to measure retreat at four representative sites
(5) to analyze the statistical relations between coastal retreat rate and climatic variables, and
(6) where possible, to develop a statistical basis for predicting the response of the coastline to potential climate changes resulting from global warming.

Definitions

Erosion, for the purpose of this report, is defined as landward retreat of cliff faces. This is the most convenient definition for use with conventional air photographs. Shoreline erosion (at the beach level) is more difficult to determine using photographs because most beaches in the region are very flat and water level changes due to storm surges are poorly documented. Surges can inundate large parts of the low-lying coast. It is important to note that cliff retreat is not directly coupled to sediment movement along the beach and shoreface, but is mediated by the rate at which sediment can be transported away from the cliff toe. An interval of rapid cliff recession resulting from thermal instability or block failure can be followed by a period of slower retreat as material is removed from the base of the cliff by waves and currents.

In addition to measuring linear rates of coastal recession, we have also examined cliff retreat in terms of volumetric land loss (VLL) in cubic metres. This refers to the volume of material above the water line which is removed by erosion processes acting at the site. In the Beaufort Sea region, it typically exceeds the sediment production because a portion of the volume loss is in the form of massive or other excess ice. The VLL for a given time interval is obtained by multiplying the area of land loss by the average cliff height at the site. It is expressed either as total loss, TVLL, between air photo missions or as an annualized loss, AVLL = TVLL/(Δt), where Δt is the number of years or part-years between photographs.

Erosion determined by ground surveys

Ground measurements of cliff retreat have been made by personnel of the Geological Survey of Canada, various universities, and exploration companies or their contractors over the past 20-30 years (e.g. McDonald and Lewis, 1973; Forbes and Frobel, 1985; Gillie, 1987, 1989; Lussenburg, 1988; Héquette and Barnes, 1990; Hill and Frobel, 1991; Solomon et al., 1992, 1993). The work has not been carried out in a systematic fashion because of variations in funding and other factors. In some cases, rapid erosion has obliterated monitoring sites before they could be resurveyed. In other cases where markers have been preserved, long sampling intervals have yielded good information on mean retreat rates but little insight on short-term variance or response to specific weather events or other factors. In addition, the number of point measurements within sites is generally limited (cf. Forbes and Frobel, 1985). Nevertheless, the accumulated results of these studies provide solid data for comparison with erosion estimates by other methods (see below) and general indications of regional and temporal variations in erosion rates.

Erosion determined from air photo analyses

Comparison of air photos provides a method for measuring cliff retreat historically and over a wider area than ground surveys. This method is limited by the availability of photography and the scale at which it was flown. Unfortunately much of the early photography in the Beaufort Sea region was shot from very high altitudes with attendant reduction in the resolution of the images.

The earliest air photographs of the Canadian Beaufort Sea coast date from the 1930s at some sites (Mackay, 1986) and the 1940s or 1950s elsewhere (Table 1). Later photography is available from the early 1950s and once or twice per decade since 1970, except at Tuktoyaktuk where there is much more frequent coverage. In 1992, we carried out 1:6000 scale photography over surveyed ground targets at most of our erosion monitoring sites (Fig. 1; Solomon et al., 1993).

Measurement of coastal recession

Analog analyses

Published information on coastal recession in the Beaufort Sea includes data obtained using one of three analog methods. These were direct measurements on uncorrected air photographs, use of a zoom transfer scope to bring photos to a common scale, and use of an analog stereo plotter to adjust for tilt. In the first two cases (e.g. Harper et al., 1985; Héquette and Barnes, 1990; Ruz et al., 1992), measurements were made from the cliff edge to common inland points (typically ice-wedge polygon intersections), but scale distortions arising from tilt or other causes were not removed. In the third case (G. Mizerovsky in McDonald and Lewis, 1973), measurements were made between plotted shorelines and include beach adjustments and any errors arising from different water levels. These measurements were not tied to any geodetic control.

Conventional photogrammetric analyses

A base map for the Tuktoyaktuk site was produced under contract using conventional air photogrammetric methods of high precision, including the use of digital stereoplotters and aerial triangulation. This is the most accurate method for obtaining geometrically and geographically correct coastlines. Once the photograph was controlled and adjusted for distortion due to parallax and lens aberration, relevant features were digitized directly into a Geographic Information System (GIS - in this case CARIS). New information was easily added to the controlled digital basemap. This accurate but relatively costly mapping and control method was used to evaluate the digital rectification procedure described next (cf. Appendix A).

Digital image rectification

In order to compare photographs taken at different scales and along different flight paths, we have developed an alternative digital processing method. Photographs were scanned at resolutions varying from 150 to 800 dots per inch (DPI), depending on photo scale, and were registered and rectified to a common scale in the public-domain GIS GRASS (Geographical Resources Analysis Support System). This system was implemented on a Hewlett Packard workstation under the Unix operating system. The precision with which measurements of cliff retreat could be made was a function of the scanning resolution and the scale of the photography. Low-altitude photography (scales of 1:15,000 and better) scanned at 300 dots per inch allowed us to measure distances to about ±1 m. The resolution was poorer on higher-altitude photos (±4 m), although this was offset to some degree by scanning at higher DPI up to the limit of the photographic resolution.

TABLE 1

Inventory of air photographs used in this study.

year	date	line	frames	approximate scale
Tuktoyaktuk				
1947	Jul-15	A10988	168	1:40000
1968	Sep-01	A20919	002-005 & 043-045	1: 6000
1974	Jul-30	A23850	030 & 060	1: 7000
1978	Jul-26	A26004	145-146 & 156-157	1: 7600
1979	Jul-25	A25223	068-070	1: 7250
1980	Aug-24	A25591	211-213	1: 5000
1982	Sep-22	A26176	012-013 & 036	1: 4000
1983	Jul-04	A26357	019	1: 5100
1984	Jul-28	A26551	008-010	1: 5000
1985	Aug-29	A26807	029-031	1:10400
1986	Aug-26	A27023	155-158	1: 4000
1992	Aug-06	GSC92002	243-244	1: 6000
North Head				
1947	Jul-15	A10988	156-157	1:41000
1950	Aug-24	A12854	323	1:39000
1972	Jul-31	A22974	098	1:54000
1974	Jul-14	A23757	132	1:60000
1985	Aug-07	A26754	199	1:60000
1992	Aug-06	GSC92002	020-023 & 070-072	1: 6000
Tent Island				
1952	Aug-06	A13470	029	1:70000
1954	Aug-80	A14365	002	1:70000
1972	Aug-03	A22975	111	1:54000
1974	Aug-07	A23838	170	1:54000
1992	Aug-06	GSC92001	003-008	1: 6000

Kay Point

1952	Aug-06	A13383	151	1:70000
1954	Aug-22	A14406	050	1:70000
1970	Aug-15	A21826	226-227	1:12500
1972	Aug-04	A22975	057	1:54000
1974	Aug-07	A23838	130	1:54000
1976	Jul-13	A24502	172	1:54000
1985	Aug-08	A26780	071-072	1:30000
1992	Aug-06	GSC92001	032-039 & 044-045	1: 6000

The rectification procedure used an affine transformation to "rubber sheet" the image to the new coordinate system. In the process of transformation, Scaling and reduction of photographic distortion were accomplished under this transformation, but some resolution was lost in the process.

At Tuktoyaktuk, recent high quality maps at a favourable scale were used to control the digital rectification procedure. Easily identifiable points such as building corners and road intersections were digitized into a map layer and the digitally scanned images were rectified to the same coordinate system. In the other locations, accurate geographic control was difficult to obtain, so common control points were chosen on each of the images, which were rectified to a reference image. This was considered a reasonable compromise because the position of the coastline relative to easily recognizable control points was more important than absolute geographic location. Measurments of cliff recession were made at points spaced approximately 100 m apart and areas of land loss were measured as well.

STUDY SITES

Four sites were chosen for analysis in this study, based on availability of suitable aerial photography and the need to consider a variety of coastal settings in the Beaufort Sea region. The sites selected are Tuktoyaktuk, North Head, Tent Island, and Kay Point (Figure 2), all of which have been monitored by the Geological Survey of Canada for varying lengths of time.

Tuktoyaktuk

This is the only permanent settlement along the coast. It is home to about 400 people and supports a large proportion of the offshore exploration facilities in the region. This site (Fig. 4) is representative of the southern Tuktoyaktuk Peninsula coast and has been battling coastal erosion for more than two decades. Tuktoyaktuk is unique in the region for many reasons, not the least of which is the existence of a detailed time series of high-resolution air photographs dating back to the late 1960's.

Erosion at Tuktoyaktuk is partly controlled at present by a sandbag seawall, originally installed in 1987. Prior to that, the only documented shore protection measure was an experiment using Longard tubes in front of the now-abandoned school in 1976 (Shah, 1978; Shah, 1982). Long-term estimates of coastal erosion at the site are about 1.8 m a^{-1} (1950-1972; Harper et al., 1985). Individual major storms have been reported to cause erosion amounting to about 3 m in 48 hours in 1970 to 3.6 m in

72 hours during a storm in 1985 (Aveco, 1986).

Rampton and Bouchard (1975) compared air photographs of the site taken in 1935, 1950 and 1971 to assess the extent of erosion. They also reported an account of more than 45 feet (13.7 m) of erosion during the storm of 14 September 1970. Winds during this storm reached 112 km h^{-1} (31 m s^{-1}).

The nearshore slope at Tuktoyaktuk is relatively steep (about 0.04 to the 1.2 m isobath and 0.014 to the 3.3 m isobath), but the bottom of Kugmallit Bay further seaward is relatively shallow (40 km to the 10 m isobath). Prior to installation of shore protection, the coast consisted of ice-rich cliffs up to 6 m high, fronted by a narrow gravel beach. The cliffs were composed of thin peat overlying sand, gravel, and diamict. Extensive site investigations have identified a large body of massive ice (0 to 5 m thick) which straddles mean sea level (Kolberg and Shah, 1976). This ice is found to pinch out seaward about 100 m from the shoreline. Subsidence resulting from thermal degradation of this massive ice has been identified as a probable cause of the rapid erosion experienced along this coast (Kolberg and Shah, 1976; Aveco, 1986).

North Head

This site is the most exposed part of the outer Richards Island coastline. Coastal retreat is occurring along ice-rich cliffs characterized by dramatic thermokarst thaw failures and rapid areal and volumetric land loss.

North Head has been extensively studied because of its proximity to a proposed pipeline from the Amauligak oil discovery offshore. Geotechnical investigations by the Geological Survey of Canada have documented thermal characteristics and stratigraphy at actively eroding and stable sites around the exposed headland (Kurfurst, 1988).

The North Head site consists of ice-rich cliffs between 5 and 15 m high. Sections of ice-rich upland tundra composed of sands and diamicts alternate with drained lake basins containing organic-rich silts and diamicts. The diamicts are very muddy and contain little gravel. The lake basins are somewhat lower in elevation than the upland tundra. The ice content by volume of the North Head coast is about 53%, of which 17% is excess ice (Dallimore and Wolfe, in prep.). Massive ice in the form of wedges and lenses comprises about 22% of the total volume of ice, the remainder being in the form of segregated and pore ice. Retrogressive thaw failures (both active and inactive) are common around the headland. Block failure and sediment transport by waves and currents are active erosion processes. A nearshore bar system is present within about 500 m of the shoreline. Downdrift of the eroding cliffs a large spit complex has formed. The nearshore gradient to the 8 m isobath is about 0.0005.

Tent Island

This site represents the rapidly retreating modern Mackenzie delta front. It has been identified as the location which is suffering the most rapid erosion along the Beaufort Coast - more than 20 m/yr (Harper et al., 1985).

Very low (1 to 1.5m) delta-front scarp in organic silts. The depositional beach is comprised of organic detritus; the intertidal zone consists of mud and organic debris. Large driftwood trees are present within 300m of the coast indicating raised water levels due to storm surge or river flooding. A storm in 1970 was responsible for the loss of two lives on Tent Island due to storm surge. Water levels were estimated to be 12 feet above mean sea level although this may be too high when compared to measured water levels at other locations in the vicinity (Wilson, 1970). The slope of the coastal zone out to the 1.5 m isobath is 0.0008 (0.0002 to the 8 m isobath).

Kay Point

This site, located on the Yukon coast, was the focus of detailed investigations in the 1970s (Lewis and Forbes, 1975; Forbes, 1981). These included a sediment budget study of the Babbage River delta and estuary system and coastal surveys around Kay Point and along the spit.

The coast at Kay Point consists of cliffs approximately 6 m high, often undercut and dominated near the point by collapse of ice-wedge polygon blocks. Erosion rates measured from 1952 and 1970 air photography average 2.7 m a^{-1} (McDonald and Lewis, 1973). The most rapid erosion is occuring at the northernmost point where wave activity is most concentrated. The shoreface slope out to the 8 m isobath varies around the point from about 0.004 at the point to 0.007 to the southeast where the land begins to rise rapidly. The generalized stratigraphy near the point is sandy gravel at the waterline overlain by several metres of sand and capped by about 1 m of peat. Undercutting and block failure is the typical mode of erosion along this section of the coast. Further southeast along the coast, the steep backshore slope rises to more than 90 m and is characterized by extensive retrogressive thaw failures.

REGIONAL DATA ANALYSIS

Regional parameters discussed in this section are those which are common to all of the study sites. They include wind speed and direction, storm frequency and duration, river discharge, water level, and temperature and precipitation. Because we are using these parameters as indices rather than as inputs to physical models, the fact that they vary to some extent over the study area is considered to be of secondary importance.

Storm selection criteria: wind speed and duration

The storm list compiled for this report (Appendix B) was extracted from the AES database (LAST.wind) for the Tuktoyaktuk DEW-line station. This database extends back to 1958 and consists of observations every six hours. Storms were defined as wind events occuring between June 1 and October 31 (the approximate maximum duration of the open water season) for which wind speed exceeded 37 km h^{-1} (10.3 m s^{-1}) for durations of more than 6 hours. The query extracted 212 storm events between 1959 and 1992. Storm durations ranged from <12 to <54 hours and maximum wind speed ranged from 37 to 72 km h^{-1} (10 to 20 m s^{-1}).

Meteorological data from the Komakuk and Shingle Point DEW-line stations were also examined. Although these data sets only extend back only to 1974, the general trends in storm frequency are similar to those found at Tuktoyaktuk. We have therefore made use only of the Tuktoyaktuk data in the following analyses. Storm statistics presented in other reports (e.g. Eid and Cardone, 1992) differ in some respects from those given here. The differences are due in part to the use of offshore data, which indicate storms of greater severity and longer duration than those observed at the coast and in part to differences in the criteria for defining a storm. The Eid and Cardone (1992) study represents a more comprehensive evaluation of storm frequency than was performed for the present study. However, the use of the offshore windfields presented in that report to generate coastal wavefields would have required the application of a wave shoaling model for each event at each location. It was felt that at this stage in the analysis, that the relative storm intensities based on the coastal winds at Tuktoyaktuk were sufficient to provide a reasonable indication of changing storminess through time. There is also some question about the technique used by Eid and Cardone (1992) of combining closely spaced events when dealing with coastal wave generation and erosion. Personal experience indicates that wave-induced erosion events and attendant storm surges rarely last more than 1 to 3 days whereas a considerable number of events listed by Eid and Cardone (1992) exceed 100 hours (4 days) and 10 events since 1970 which exceed 200 hours. Dissapation and storm surge relaxation between several short, but closely spaced events reduce the overall wave energy available for erosion at the coast. For storms present in both the Eid and Cardone (1992) database and this report, maximum observed offshore winds are about 1.5 times stronger that those measured at Tuktoyaktuk.

Storm wind directions are calculated as the vector average of the wind direction at the beginning and end of each storm event. As has been recognized by other workers (e.g. Hill et al., 1991; Harper and Penland, 1987), the dominant storm winds come from the west and northwest with a secondary mode from the east and northeast. Over the 33 years of record, the total open-water storm duration has varied considerably. The average annual duration of storms occurring during the June to October interval is 80 hours, with a standard deviation of about 42 hours. A distinct reduction in storm activity extended from the mid-1960s to the end of the 1970s. In contrast, the 1980s appear to have been particularly stormy. This is most clearly seen in a plot of the residuals (Fig. 7), where the largest annual departure from the mean occurs in 1981 and almost all years in the 1980s exhibit positive residuals.

TABLE 2

Storm Database Statistics

	maximum wind speed (km/hour)	**duration** (hours)
mean	46	13
median	45	7
mode	37	7
std dev	8	9
minimum	37	6
maximum	72	49
count	212	212

As seen in Figure 9, more than 70% of the storm events exhibited maximum wind speeds of less than 50 km h^{-1} (14 m s^{-1}). Relatively rare events (<10% recurrence frequency) are responsible for wind speeds in excess of 60 km h^{-1}.

Mackenzie River discharge

The Mackenzie River above Arctic Red River supplies 90% of the average annual inflow to the Mackenzie Delta (Hirst et al., 1987; data courtesy of Inland Waters Directorate, Environment Canada). Peel River and Arctic Red River supply 8% and 2% respectively. Unfortunately the gauging record at Arctic Red River extends back only to 1973. A longer record, going back to 1938, is available for Mackenzie River at Fort Simpson, about 400 km upstream. Linear regression of the monthly discharge of Mackenzie River above Arctic Red River on the same at Fort Simpson, for the years 1973 to 1988, indicates that the Fort Simpson discharge provides a reasonable surrogate for discharge to the delta for the months of July to October. Correlation coefficients range from 0.9 in July to 0.4 in October. The correlation in June is poor, probably because of the variable timing of spring runoff in different parts of the drainage basins.

The mean seasonal discharge (June to October) was lower than average during the years 1951-1955, 1968-1971 and 1980-1984 (Fig. 10). Monthly discharge data show that the highest runoff and maximum variance typically occur in June, associated with spring breakup in the delta and snowmelt runoff from large parts of the drainage basin. August 1974 was notable for unusually high discharge, when salinities in coastal waters of the Beaufort Sea remained low throughout the summer (Forbes, 1981). On the other hand, discharge was particularly low in July during the years 1980 to 1983.

Water levels

Positive storm surges raise water levels and facilitate erosion by permitting larger waves to reach the coast and enabling waves to attack higher on the shoreline. Whereas the tidal range at Tuktoyaktuk is 0.5 m or less, log lines suggest a maximum surge level of about 2.4 m (Harper et al., 1988). This is believed to be the level associated with a severe storm in September 1970, when Tent Island was completely inundated and extensive flooding was reported elsewhere along the coast (Department of Public Works, 1971). On the other hand, the maximum storm surge recorded at Kay Point on the Yukon coast is less than 2 m and was associated with a different storm earlier in the 1960s (Forbes, 1989). A major storm in 1944 is said to have generated a storm surge of almost equivalent magnitude (Department of Public Works, 1971).

The record of water levels at Tuktoyaktuk dates back to 1961, but is very intermittent and unfortunately the gauge was not functioning during the 1970 storm. Short-term records are available from several other sites during the mid-1970s (Henry, 1975; Forbes, 1981).

Storm surge elevations in the Beaufort Sea are a function primarily of wind stress and direction as opposed to atmospheric pressure as well as water depth, and coastal configuration (Henry and Heaps, 1976). In general, winds blowing from the west and northwest cause positive surges along the Canadian Beaufort coast (Fig. 11), with maximum water levels in Kugmallit and Mackenzie Bays. Negative surges are primarily associated with easterly winds. The largest surges are positive (>1.6 m) and are associated with wind directions between 270° to 300° and wind speeds in excess of 55 km h^{-1} (15 m s^{-1}). At lower surge levels, the relations are less clear and water levels may also be affected by atmospheric pressure variations and Mackenzie River discharge.

Although work in other areas has demonstrated a link between water-level fluctuations and coastal recession (e.g. Orford et al., 1991, 1992) and similar effects are likely to be present in the Beaufort

Sea region, the intermittent record of water levels at Tuktoyaktuk precludes an analysis of this kind in the study area.

Air Temperatures

Air temperatures may affect coastal erosions rates in areas of permafrost by raising or lowering the summer thaw depths thus alteringthe strength profile of coastal sediment bluffs. The temperature records span the period from 1957 to 1990. Daily mean temperatures were used to calculate monthly means for each year for each of the open water months. Mean positive temperatures are prevalent in the months of June, July, August, and September. Temperatures are generally below freezing from October onwards. July and August are the hottest months of the year. August and October exhibit the greatest range and variance.

TABLE 3

Monthly Open Water Season Temperatures

	June	July	Aug	Sept	Oct
mean	5.4	10.7	9.3	2.8	-7.7
s.e.	0.29	0.33	0.39	0.31	0.45
median	5.5	11.2	8.7	2.7	-7.4
std dev	1.71	1.92	2.29	1.81	2.62
range	7.0	8.2	10.7	6.4	10.7
minimum	1.7	6.0	5.5	-0.5	-13.85
maximum	8.7	14.2	16.2	5.9	-3.2
count	34	34	34	34	34

The annual departures from the seasonal (open-water) mean temperature suggest cooler times during the 1960s and early to mid 1980s, with somewhat warmer temperatures prevailing in the 1970s and late 1980s (Fig. 12). These trends are also present in the melting-degree-day index (Ice Climatology, 1991 and may be related to general circulation patterns on which storm frequency and intensity depend.

Precipitation

According to Hirst et al. (1987) there have been no persistent trends in the amount of precipitation recorded at Tuktoyaktuk between 1948 and 1984. However, the 1970s are notably drier than the mean annual total precipitation for the period of record whereas the 1950s to 1960s and the early 1980s are wetter. These data indicate that there could be some correlation between erosion and preciptation although it is also likely that the relationship is based on the fact that storm systems responsible for high winds are accompanied by rain. The likely dependence of precipitation on storms precludes an assessment of its independent effect on coastal erosion.

Ice distribution and open-water fetch

The sea-ice distribution during storms is important in that it limits the effectiveness of the winds to generate waves. The ice edge is rarely abrupt, however, and can be defined in terms of various concentrations ranging from 1/10 to 10/10 areal coverage. In this study, we take the 3/10 ice edge as the limit at which wave formation is significantly limited by ice (cf. Pinchin et al., 1985).

Weekly ice charts have been analyzed for the week prior to each storm event. The distance to the 3/10 ice edge from each of the four study sites has been measured in 22.5° increments. Effective fetch is defined (following U.S. Army Corps of Engineers, 1977) as

$$F_{eff} = \{\Sigma[X_i \cdot (\cos \propto)]\} \ / \ \{\Sigma[\cos \propto]\} \qquad [1]$$

where X_i is the radial distance to the ice edge and $\propto$ is the angle between the wind direction and the fetch direction, for all directions ±45° from the wind.

Effective fetch at Tuktoyaktuk is limited by the presence of land to the east, such that easterly storms have very little impact there. Figure 13 displays the time series of effective fetch for all storms in the Tuktoyaktuk database. While there is no obvious pattern, there are intervals (e.g. 1966 to 1968) when the presence of ice or predominance of easterly storms produced fetch-limited conditions. Effective fetch at North Head differs from that at Tuktoyaktuk in that the site is more open to easterly storms but is closer to the southern limit of the Arctic pack ice. Distinctive occurrences of large fetch at North Head were associated with storms in 1972-1973, 1981-1982, and 1987. Low effective fetch distances prevailed 1963-1964, the mid-1970s and 1983-1985. At Tent Island, on the western front of the Mackenzie Delta in Mackenzie Bay, the fetch is limited by land to the northeast, east, south and southwest. This site is open to the dominant storm winds from the west and northwest. The time series of effective fetch at Tent Island is broadly similar to that at Tuktoyaktuk. Effective fetch at Kay Point reflects the closer proximity of the Arctic ice pack along the Yukon coast. Fetch is also limited to the west by Herschel Island, although some wave energy from the west is retained by refraction around the island (Forbes, 1981).

Wave energy and storm intensity

The coastal response to wind and fetch variations is largely a function of the wave energy generated during each storm. Significant wave height, H_s, has been hindcast for this study using the Sverdrup-Munk-Bretschneider (SMB) method for deep water waves (following Fleming et al., 1984; after Bretschneider, 1973):

$$H_s = \{0.283 \cdot \tanh[0.0125 \cdot (gF/U^2)^{0.42})]\} \cdot \{U^2/g\} \qquad [2]$$

where g is gravitational acceleration, U is the wind speed, and F is the effective fetch.

Although equation 2 may be expected to overestimate wave height in the shallow coastal zone of the Beaufort Sea, nevertheless it provides a useful index of wave energy. Bottom drag and wave breaking effects, particularly over the shallow waters of Kugmallit Bay and the subaqueous Mackenzie Delta, lead to severely reduced wave heights at the coast (cf. Pinchin et al., 1985). As discussed early, the use of the wind data from the Dewline Station at Tuktoyaktuk represents a significant underestimate of the true offshore windfield. It is used here only to provide an index of storm intensity rather than an accurate hindcast of actual wave heights.

The deepwater wave height computed using equation 2 for the severe storm of 14 September 1970 was

5 m. Two small vessels in open water between Tuktoyaktuk and the ice edge reported wave heights of 25 feet (7.6 m) in 80-100 knot (150-185 km h^{-1} or 41-51 m s^{-1}) winds. Observers at Tuktoyaktuk reported waves of 8 feet (2.5 m) superimposed on a storm surge of similar magnitude. In other words, the deepwater wave computed using equation 2 was similar to the reported deepwater wave height, but by the time the waves reached the coast they had diminished by a factor of three.

The product of wave height and storm duration can be used as an indicator of storm intensity. The annual sum of storm intensities and the sum of intensities between photographs provide measures of variability in the incidence of wave energy at the coast. Storm intensity values incorporate the effects of varying storm frequency, wind speed and direction, and ice distribution.

Wave heights and storm intensities have been computed for each storm event at each of the study sites. At Tuktoyaktuk (Figs. 14, 15, 16), the years 1966-1968 and 1973-1979 stand out as particularly quiet intervals. In contrast, the 1980s were a much more stormy decade, comparable to the early 1960s. The severe storm of September 1970 stands out in the wave height time series, but the storm intensity was limited by its short duration.

The storm intensity distribution at North Head is quite similar to that at Tuktoyaktuk (Fig. 16). The years 1981, 1984 and 1987 represent intensely stormy recent intervals. The years 1960 and 1963 were nearly as stormy while 1973 to 1980 were very quiet. Higher intensities at North Head during the mid- and late-1960s may result from more frequent easterly storms (from which Tuktoyaktuk is protected) or from greater open-water fetch distances to the west and northwest.

Annual storm intensity at Tent Island is very similar to Tuktoyaktuk and North Head. In contrast, the storm intensities at Kay Point are much lower than at the other three sites. This is especially obvious during the stormy 1980s, when the storm intensities at Kay Point were not appreciably higher than during the 1970s (Fig. 16).

COASTAL RECESSION

Site 1: Tuktoyaktuk

Cliff Recession

Cliff recession was measured at Tuktoyaktuk using a combination of conventional analog and digital photogrammatric methods (see Appendix A). The analog photogrammetry was carried out under contract by the Eastcan Group of Survey Consultants Limited. Common points on all photo sets were chosen to faciliate registration and the 1985 photography was matched to the aerial triangulated control on a Wild A8 stereoplotter. The control was provided by the Surveys and Mapping Branch of Energy Mines and Resources Canada (now Natural Resources Canada). Cliff lines were mapped into a GIS for subsequent analysis. Photography flown between 1947 and 1986 was employed. Although more recent photographs are available, the advent of shore protection in 1987 makes them useless for the purpose of this study. High-altitude photography in 1972 and 1950 was deemed to be of insufficient resolution and was omitted from the analysis. True ground positions are considered accurate to within ±0.3 to ±0.6 m for the low-altitude photography (1968 to 1992) and to within ±3.0 to ±4.0 m for 1947 and 1950.

During the process of measuring cliff recession it became apparent that erosion varied considerably along the 900 m stretch of shoreline fronting the Tuktoyaktuk townsite. The site was therefore subdivided into five zones, as follows: (1) Flagpole (300 m), (2) North Town (125 m), (3) South Town (200 m), (4) Cemetery (80 m), and (5) Schoolhouse (195 m) (Fig. 3). The zones range from about 80 m to 300 m in length. Cliff heights average about 6 m at Flagpole, Cemetery and Schoolhouse and about 2-3 m at the North and South Town sites. Areas of land loss (in square metres) were measured for each air photo interval in each zone and multiplied by the average cliff height to obtain a total volumetric land loss (TVLL). This number was then divided by the number of years between photographic missions to determine the annual volumetric land loss (AVLL) in cubic metres per year (Fig. 17).

All measurments were made from the 1947 cliff line and interval variations were calculated by subtraction. Table 4 gives the AVLL for each zone. Volume errors are estimated by multiplying the positional accuracy by the length of each zone and the average cliff height, then dividing by the number of years over which the estimate is made. Volume error estimates range from 65 m^3 to 1600 m^3 depending on the zone of measurement (its length and height) and the number of years between measurments. This method is very conservative in that it demands that **every** point along the cliff-line be offset the maximum possible amount in the direction of error. In all likelihood, the errors along the cliff-line would tend to cancel each other out rather than add together. This is corroborated by the similarity in shape of the recession curves for each zone, suggesting that despite the relatively large potential errors at low recession rates, the actual errors are much smaller. The AVLL between zones varies by an order of magnitude, from less than 1000 m^3a^{-1} (1.2 $m^3a^{-1}m^{-1}$) to more than 10,000 m^3a^{-1} (12 $m^3a^{-1}m^{-1}$). The average for the period from 1947 to 1986 is 4000 m^3a^{-1} (5 $m^3a^{-1}m^{-1}$).

TABLE 4

Erosion (AVLL) at Tuktoyaktuk

Year	Flagpole	North Town	South Town	Cemetery	Schoolhouse
47-68	2363± 594	66± 98	301± 165	40± 149	649± 295
68-74	3230±1300	190± 215	417± 360	360± 325	1050± 645
74-78	1080± 390	-75± 65	15± 108	75± 98	-285± 194
78-79	1200±1560	200± 258	0± 432	-60± 390	180± 774
79-80	120±1560	-260± 258	540± 432	120± 390	60± 774
80-82	5790± 780	1020± 129	1740± 216	660± 195	840± 387
82-83	600±1560	20± 258	100± 432	-180± 390	60± 774
83-84	1560±1560	-220± 258	480± 432	180± 390	-60± 774
84-85	2640±1560	340± 258	1020± 432	420± 390	-120± 774
85-86	5760±1560	840± 258	1380± 432	1020± 390	2100± 774

During several intervals when recession was small, negative values were measured, meaning that the cliff grew seaward. This is an apparent impossibility and results from a combination of factors. The North Town zone consists of a low cliff with a rounded top and has been subject to washovers in the past. The detailed recession history at this site is complicated by the difficulty in discerning the edge of the cliff. In general, this zone comprises less than 10% of the total volumetric land loss in any given time interval. The Schoolhouse zone has been the scene of experiments in shore protection beginning in 1973. The negative excursion from 1974-1978 may be related to that experiment. The cause of the Cemetery zone negative excursion in 1982-1983 may simply be a measurement error. In general, more than 60% of the volumetric land loss in any air photo interval is attributable to erosion at the Flagpole zone, the most exposed part of the coast.

The alongshore variation in AVLL is illustrated in Figure 18. This clearly shows the much higher rates of erosion in the Flagpole zone relative to the rest of the Tuktoyaktuk shoreline. Although the rates are lower in the South Town and Cemetery zones, they show a similar distribution over time. The Schoolhouse and North Town zones are somewhat different for the reasons mentioned above.

Cliff recession in relation to storm intensity at Tuktoyaktuk

At the outset of this investigation it was postulated that storms were the main forcing mechanism driving the cliff recession at coastal sites throughout the Canadian Beaufort Sea. In order to investigate the relation between cliff recession and storminess, the storm intensity index (i.e. the sum of the products of maximum significant wave height and duration for each storm) was recalculated for each interval between air photographs. The correlation between volumetric erosion and storm intensity clearly evident in Figure 19. When the average annual land loss (AVLL) is examined in relation to annual storminess (Fig. 20), it becomes quite apparent that there is a need for as detailed a time series as possible. Substantial variation in storm intensity from 1959 to 1974 is averaged out by the relatively long interval between photographs. A similar phenomenon is seen in the 1980 to 1982 interval. Very rapid cliff recession in 1981 is probably due to the intensely stormy year of 1981, after which 1982 was relatively quiet.

In order to evaluate the effects of averaging, a 6-year average recession rate was calculated for each zone and compared with averaged storm intensity over the same intervals (Fig. 21). While the lowest intensities correspond to small recession rates, the periods of high recession are associated with dramatically different intensities. While not surprising, this suggests that it may be difficult or impossible to establish a relation between coastal recession and storminess at sites where detailed time series are unavailable.

Cliff recession in relation to Mackenzie River discharge and air temperature

Mackenzie River discharge and air temperature may influence erosion along the Beaufort Sea coast by destabilizing permafrost. Mackenzie River water attains temperatures in excess of 15°C at Arctic Red River (Hirst et al., 1987). Surface water temperatures in coastal waters between Herschel Island and Liverpool Bay are typically between 5°C and 11°C (Herlinveaux and de Lange Boom, 1975). Frozen sediments and massive ice can thaw rapidly when subjected to these temperatures (cf. Mackay, 1986; Kobayashi and Atkan, 1986). Despite limited inter-annual variation in Mackenzie River temperatures, the reduced freshwater volume in low-flow years might be expected to decrease the effectiveness of thermal erosion along the coast. In fact, there does appear to be some correlation between increased erosion and **lower** annual discharge in Mackenzie River (Fig. 22).

Similarly, higher air temperatures melting-degree-days may be expected to affect the stabilty of the cliffs by increasing the depth of thaw. The resulting instability of the active layer may contribute to mass movement on cliff faces along the coast. However, there is no clear relation between cliff recession rate and the melting-degree-day index (Fig. 23). The implication is that variations in the thickness of the active layer play only a small role in cliff recession. Therefore, rapid cliff recession during stormy periods must result from mechanical erosion and thaw produced by wave action and storm surge activity. During intervals when subaerial thaw supplies material to the cliff toe, the result may be armouring and insulation of the frozen sediments beneath the beach. Further erosion will depend on the ability of storm waves to remove this material, exposing the frozen materials beneath to thermal erosion by the warm sea water.

Discussion of cliff recession at Tuktoyaktuk

Cliff recession rates at Tuktoyaktuk are highly variable alongshore and through time. To a large extent, however, changes in recession rates are synchronous along the coast -- in general, increased rates of recession are found along all sections of the coast during the same time intervals. The recession rate is found to be reasonably well correlated with storm intensity and uncorrelated with air temperature or river discharge. As a general rule, increased storm intensity is accompanied by increased cliff recession. While this might be considered obvious, the detailed mechanisms are less clear.

Figure 24 shows changes in the shore profile in the Flagpole zone between the 1975 and 1992. These changes include a steepening of the nearshore profile seaward of the sandbag seawall constructed after 1987. Comparison of 1980 and 1982 air photographs indicates rapid erosion over the two-year interval. Whereas 1981 was unusually stormy, 1982 was a relatively quiet year. We have no information on the exact timing of the erosion response during the 1981-1982 interval. However, the two low-intensity years 1982-1983 were accompanied by very low erosion in 1983. In the following years, the storm intensity increased to a peak in 1985, while cliff recession increased slowly through 1986, a year of slightly diminished intensity. This suggests a lag effect under some circumstances. Four processes which could be responsible for this effect are armouring at the cliff toe (cf. Dallimore and Wolfe, in prep.), varying rates of thermal degradation (Mackay, 1986; Kobayashi and Atkan, 1986), sediment entrainment by ice during freezing storms (see e.g. Kempema et al., 1989; Forbes and Taylor, in press), and profile readjustment to ice scour on the shoreface (cf. Héquette and Barnes, 1990).

Armouring at the toe of the cliff may follow undercutting and slumping of large blocks of material which are still frozen. This has been observed along other parts of the coast including North Head (Dallimore and Wolfe, in prep.) and Kay Point (Lewis and Forbes, 1975). These blocks can take some time to degrade and may prevent further erosion until they have melted and been removed. However, this does not appear to be an important factor at Tuktoyaktuk. There are no photographs in which large blocks of material are observed and the small talus accumulations at the base of the cliffs show no systematic relation to trends in cliff recession (as might be expected to if the talus were armouring the cliff toe).

Thaw consolidation due to melting of massive ice at the shoreline has been hypothesized as a principal cause of coastal erosion at Tuktoyaktuk (Shah, 1978). The reasoning is that consolidation due to thawing of massive ice 3 to 6 m thick (at and just below the waterline) can cause settlement of up to 5 m (Aveco, 1986). Such settling would steepen the shoreface to allow incursion of larger waves, among other factors. The time required for thaw and consolidation to occur depends on the water temperature, turbulence, and thickness of overburden (Mackay, 1986; Kobayashi and Atkan, 1986). Using a simplified equation, Mackay (1986) estimated a thaw rate of about 0.9 m a^{-1} for materials with high ice content exposed to mean annual water temperatures of 2°C. This calculation assumes that there is little thawed overburden to act as an insulating blanket over the massive ice. Harper et al. (1978) measured July-August thaw rates of close to 10 mm per day on beaches along the Alaskan

Chukchi Sea coast. They calculated increases in thaw depth of 100 mm in 24 hours as a result of storm surge. In other words, the rate of thaw of an ice-rich shoreline may be on the order of 1 m a^{-1} with higher rates occuring when storm surges raise water levels and remove insulating overburden.

Erosion resulting from severe storm events at Tuktoyaktuk has been reported to be as high as 13 m (up to 3.6 m according to Aveco, 1986; reports of 13 m cited by Rampton and Bouchard, 1975). Even under conditions of rapid thaw penetration during storm surge, erosion rates of this magnitude could result in the formation of a shallow sloping platform of frozen material. Every winter, in water depths less than about 2 m, ice freezes to the seabed and the bottom sediments freeze to variable depths depending on the time spent in contact with the ice. If massive ice degrades at a rate of about 1 m a^{-1}, it will be at least two years before the depth exceeds 2 m and continuous thaw can occur. This could account in part for the lag between storm intensity and retreat observed in the early to mid-1980s.

Entrainment of sediment by ice during freezing storms is a third factor which may affect the rate and timing of erosion episodes. This is known to be an important process along the Alaskan Beaufort Sea coast (Reimnitz and Barnes, 1987; Kempema et al., 1989; Reimnitz et al., 1993), but has not been documented in the Canadian Beaufort Sea (Forbes and Taylor, in press). Concentrations of sediment up to 1000 m^3km^{-2} have been observed in congealing slush ice along the Alaskan coast (Reimnitz and Kempema, 1987). Freezing storms occur just before freeze-up in the fall when low air temperatures combine with waves to causing supercooling of the water column and rapid ice formation immediately following the storm. Occasional occurrences of a coastal polynya in winter (Lewis and Forbes, 1975; Reimnitz et al., 1993) provide additional opportunities for frazil entrainment. Sediments entrained during freezing storms become incorporated into the ice canopy and can be removed from the coastal zone during breakup.

TABLE 5: Regression coefficients and correlation coefficients for Tuktoyaktuk

Zone	Data Type	Slope	Intercept	R
All	Annual	28.5	+859	0.70
All	Cumulative	52.5	-1885	0.86
All	Int>10	53.1(37.3)	-1599(-246)	0.85 (0.88)*
All	Int>15	54.2(38.6)	-862(+343)	0.85 (0.90)*
All	Int>40	39.1(45.7)	+4450(+712)	0.46 (0.90)*
Flagpole	Annual	15.2	+747	0.72
Flagpole	Cumulative	31.1	-805	0.87
Northtown	Annual	2.9	-88	0.64
Northtown	Cumulative	3.6	-274	0.81
Southtown	Annual	5.3	+42	0.86
Southtown	Cumulative	6.2	-141	0.91
Cemetery	Annual	2.8	-19	0.74
Cemetery	Cumulative	3.8	-146	0.87
Schoolhouse	Annual	2.2	+177	0.29
Schoolhouse	Cumulative	7.8	-520	0.63

*Note: Cumulative intensities and erosion. Events exceeding 10, 15, and 40 units respectively. Values in parentheses exclude intervals greater than two years (1968 to 1974 and 1974 to 1978). zone during breakup (Reimnitz et al., 1993).

Although we have no information on sediment concentrations in ice near Tuktoyaktuk, we have identified potential freezing storms based on temperature and fetch conditions present during storms. Using a temperature threshold of -2°C, we have identified 19 storms with open water fetch distances of more than 50 kilometres between 1960 and 1986. Three of the storms occurred in 1970, the same year as a severe autumn storm associated with significant erosion at Tuktoyaktuk. It is difficult to ascertian the effect of these storms on coastal erosion. In general, the years in which freezing storms occur tend to be stormier than the norm and we have already demonstrated the relation between erosion rates and annual storm intensity. There is clearly a need for more field data to ascertain the effects of freezing storms on coastal erosion in the Canadian Beaufort Sea.

Finally, shoreface scour by grounding pressure ridges or during ice piling events has been suggested as a factor contributing to erosion of coastal bluffs in the study area (Héquette and Barnes, 1990). This hypothesis is based in part on a statistical analysis of cliff recession rates and other factors throughout the Beaufort Sea and on observations of ice-induced erosion at Atkinson Point. However, given the shallow shelf extending at least 30 km offshore from Tuktoyaktuk, it is unlikely that ice scour is an important influence at this site.

Statistical Analysis

Based on the qualitative observations of correlation between cliff recession and storm intensity at Tuktoyaktuk, a statistical analysis was undertaken (Table 5). Linear regressions, with AVLL or TVLL as dependent variables and annual storm intensity (ASI) or cumulative storm intensity (CSI) as independent variables, was performed on a zone-by-zone basis for the dataset from 1968 to 1986. The regression of AVLL on ASI yielded a lower slope and lower correlation coefficient than regression of TVLL on CSI. This reflects in part the masking of lag effects in the latter case.

Using the cumulative regression relations for all zones except Schoolhouse, the slope of the regression line was non-zero at the 95% confidence level and a significant trend was present at the 92-99% confidence level (based on the F statistic). As might be expected, the slope in the Flagpole zone was much greater than in any other zone. The intercepts in all zones except Flagpole and Schoolhouse were close to zero. The poor correlation in the Schoolhouse zone is consistent with the history of shore protection experiments there during the 1970s. The reasonable fit of the data to the regression model in the other zones should be interpreted with the estimation of measurement errors in mind.

A comparison of observed and predicted TVLL is presented in Figure 25.

Effects of extreme events

Descriptions of episodic cliff recession (Hume and Schalk, 1967; Rampton and Bouchard, 1975; Aveco, 1986; Dallimore and Wolfe, in prep.) suggest that erosion of unconsolidated frozen coastal sediments is largely driven by extreme events. We have examined this hypothesis by considering the relations between erosion at Tuktoyaktuk and storm intensities exceeding various thresholds (Table 5). The frequency histogram of storm intensity (Fig. 25) indicates that 50% of storms exceed an intensity of 10; 25% exceed 15 and only 10% exceed 40 intensity units. Correlation between TVLL and storm intensity was not appreciably improved by applying these higher intensity cut-off values. A slightly improved fit was found when erosion measurements based on intervals greater than 2 years were removed from the analysis. The fact that no significant improvements resulted from using higher intensity cut-off values suggests that, while extreme events are important, the cumulative impact of smaller storm events is equally effective over time. The combined effects of high water levels due to storm surge and large waves could not be investigated because of the intermittent nature of the water level record. It is probable that only those large events accompanied by high water levels cause dramatic erosion events which are remembered for years. Their relative role in longer term erosion is not clear and requires more data immediately before and after large events.

SITE 2: NORTH HEAD

Cliff recession at North Head was measured using the digital image rectification method. The air photo database is given in Table 1.

The study area was divided into five zones (A to EF) following Wolfe (1989) and Dallimore and Wolfe (in prep.). The zones (Fig. 5) consist of drained lake basins and upland tundra surfaces. Areas were measured for each of the zones and linear recession rates were measured at 100 m intervals orthogonal to the coastline. Because all but the 1992 photography was at relatively unfavourable scales, linear recession errors are on the order of ±4 m between photographs. Very large annualized linear recssion rates were recorded between 1972 to 1974 followed by largely negative recession rates from 1974 to 1985. This suggests that the rectification of the 1974 photograph was unsatisfactory and the results cannot be used.

Figure 27 shows the time history of shoreline displacement with progressive erosion of the North Head site. The average linear recession, areal land loss, and volumetric land loss (TVLL) for each of the five zones are summarized in Table 6.

TABLE 6

Linear recession at North Head (m)

	1947-50	1950-72	1972-85	1985-92	*1986-88	Type	H	L
A	10.75	15.33	18.89	16.94	19	tundra	14	490
B	4.61	7.77	8.13	20.00	19	lake basin	4	670
C	6.45	28.08	14.05	-5.07	1.7	tundra	11	290
D	8.62	7.17	5.82	5.33	5	lake basin	1	400
E+F	4.88	10.95	2.49	11.98	3.6	tundra	11	1550

*Ground measurements. H is segment height (m) and L is segment length (m).

Land loss at North Head: area in m^2 (volume in m^3)

	1947-50	1950-72	1972-85	1985-92
A	2963 (41482)	2779 (38906)	4683 (65562)	4927 (68978)
B	2137 (8548)	-1130 (-4520)	9133 (36532)	1873 (7492)
C	356 (3916)	2076 (22836)	422 (4642)	397 (4367)
D	2771 (2771)	1022 (1022)	570 (570)	-1910 (-1910)
E+F	4301 (47311)	9554 (105094)	2090 (22990)	10111 (111221)

Cliff recession is highly variable both temporally and spatially. Linear rates generally exceed estimates of error by a factor of two, indicating that trends observed are probably reasonable estimates of erosion. It is interesting to note that virtually all of the cliff recession in zones A, B, and D measured during the interval 1985 to 1992 can be attributed to a storm in late August 1987, as described by Dallimore and Wolfe (in prep.). Ground measurements in 1986 and 1988 (Gillie, 1989) at points representative of each zone illustrate the degree to which the 1987 storm dominates the erosion during this interval. This storm was of moderate to high intensity and was accompanied by a storm surge of about 1.4 m. Reports of wave heights of about 4 m at an offshore well site (MEDS Amauligak F-24 report, cited by Dallimore and Wolfe, in prep.) agree well with the hindcast deepwater waves of 3.9 m given by equation 2. The storm stands out in the annual summaries of intensity as one of several events which made 1987 one of the most stormy years on record (Fig. 16). The significance of the 1987 storm year is less apparent for zone E+F, where thermokarst reactivation dominated cliff erosion during this time interval.

Unfortunately the long intervals between photographs at the North Head site preclude a detailed analysis of the kind presented for Tuktoyaktuk in the preceding section.

SITE 3: Tent Island

Coastal recession at Tent Island (Figs. 6 and 28) was measured using the digital image rectification method. The air photo database is presented in Table 1. Apart from the 1992 photography flown specifically for this project, all photographs of Tent Island have been taken at high altitudes. In some cases it was difficult to pick out the coastline. The rapid erosion measured between 1972 and 1974 is therefore somewhat suspicious. However, shoreline recession at this site is so rapid that the high altitude photography can be compared with confidence. The measured rates of recession amount to 2 to 6 times the estimated uncertainty of approximately ±4 m. The whole northwest-facing shoreline is receding at an average rate of 9 to 22 m a^{-1} both in the long term and the short term (Table 7). The volumetric land loss along the low delta-front scarp is between 9000 and 27000 m^3a^{-1}.

TABLE 7

Erosion at Tent Island

years	erosion (m/int)	(m/a)	TVLL	AVLL	SI/int	SI/a	Q	Meltday	Temp
52-54	19	9	18150	9075			9381		
54-56	36	18	38165	19082			10550		
56-72	141	9	129635	8102	1777	127	10513	853	3.87
72-74	50	25	54341	27170	44	22	11661	868	3.22
74-92	163	9	132464	7359	2098	117	10510	948	4.40

Note: climatological data are unavailable for the first two intervals (1952-1956).

Unfortunately, as at North Head, the temporal resolution is too coarse to perform any statistical analysis. On a cumulative basis, there is a negative relationship betweeen storm intensity and cliff recession. Given the extremely shallow shoreface slope over the subaqueous delta platform, wave energy is strongly dissipated except during periods of high water levels. Water levels along the delta front are affected by river discharge as well as by wind-driven storm surges. It is possible that the water levels constitute the overriding influence on erosion rates along the delta front. Locally, the position of distributary channels may also play a role in erosion of nearshore sediments (Jenner and Hill, 1989).

SITE 4: Kay Point

Cliff recession at Kay Point was measured using the digital image rectification method. Ground measurements of linear erosion are also available from mid-1970s, 1984, 1985, 1986, and 1992 (Forbes and Frobel, 1985; Dallimore, unpublished field notes, 1985; Gillie, 1987; Solomon et al., 1993). The air photo database is given in Table 1. Most of the photography was flown at high altitude and the scales are marginal for measurement of cliff recession. Distance meaasurements are considered good to about ±4 m and areal land losses are probably with within 20% of the reported values (see Appendix A).

The results (Table 8) show TVLL varying from -2726 m^3 (effectively zero) over 2 years to more than 230,000 m^3 over a 16-year interval. AVLL values illustrate the smoothing effect of averaging over longer time intervals. Table 8 also shows the average annual and cumulative recession distances for two zones (segments 1 and 2 of Lewis and Forbes, 1975; see Fig. 7). Annual recession rates in the more exposed zone 1 generally exceed retreat in zone 2 by factors of two to six. In recent years, there has been a decrease in the recession rate in zone 1 and an increase in zone 2. This may represent a realignment of the coast following rapid erosion of zone 1 during the early 1970s.

TABLE 8

Erosion at Kay Point

years	AVLL	TVLL	zone 1 retreat (m/a)	zone 2 retreat (m/a)	zone 1 retreat (m)	zone 2 retreat (m)
52-54	26457	52913	4.6	7.8	18.3	31.2
54-70	14806	236890	1.5	0.4	23.4	6.7
70-72	49876	99752	6.6	1.1	13.2	2.3
72-74	18952	37904	3.8	1.1	7.6	2.3
74-76	-1363	-2726	1.1	0.5	2.2	1.0
76-85	18412	165706	2.6	1.7	23.4	15.2
85-92	17583	123083	2.4	1.8	17.1	12.8

TABLE 9

Storm Intensity at Kay Point

years	annual intensity	cumulative intensity	maximum intensity	intensity >25	intensity >10
54-70	54.9	878	80	496	590
70-72	60.6	121	48	48	71
72-74	18.5	37	14	26	26
74-76	15.2	30	7	0	13
76-85	49.0	441	47	263	392
85-92	58.5	409	49	99	329

Meteorological data extend from 1958 to 1991. The database is therefore incomplete for the intervals 1954-1970 and 1985-1992. These were adjusted (Table 9) by assuming that intensity levels remained the same as the mean over the interval and the cumulative data were increased accordingly.

There is no correlation between cliff recession measured at Kay Point and temperature or precipitation during the open-water season. Mackenzie River discharge for the open-water season is negatively correlated with cliff recession (R = 0.8). The connection may have something to do with the position of the ice edge responding to freshwater volumes. Manak and Mysak (1989) found a positive correlation between Mackenzie River discharge and ice extent on the Beaufort Sea shelf. High discharge years were found to precede large ice extent by about 1 year. Cursory examination of our data indicate that there is some relation between effective fetch at Kay Point and Mackenzie River discharge, but the exact nature of the link is unclear.

As is apparent in Figure 29, there is a close correspondence between cumulative storm intensity and volumetric erosion at Kay Point (Table 10). TVLL is highly correlated with storm intensity, whether the latter is adjusted or not (correlation coefficients between 0.92 and 0.94). Regression of TVLL on cumulative storm intensity is significant at the 99% level, but has a large positive intercept (representing erosion without storms). A slightly better fit is obtained by regression of TVLL on the natural logarithm of cumulative storm intensity (Fig. 30). The logarithmic fit is better because it takes into account the rapid decrease in erosion at the low end of the storm intensity scale. It also eliminates the large positive intercept. However, the linear equation produces a better fit at higher intensities and has therefore been used in the following discussion.

TABLE 10

Regression and Correlation Coefficients for Kay Point

dependent variable	independent variable	slope	intercept	correlation coefficient R
TVLL	cum. intensity	249	39577	0.944
TVLL	adj.cum.intensity	195	38723	0.921*
TVLL	ln cum.intensity			0.961
TVLL	intensity >25	417	45187	0.924
TVLL	adj.intensity >25	510	40245	0.932*
TVLL	intensity >10	347	27940	0.947
TVLL	adj.intensity >10	406	24429	0.940*
TVLL	max.intensity	3129	-17699	0.962
AVLL	ann.intensity	493	-1367	0.607

* Intensities adjusted for the fact that the meteorological database does not span the entire time interval. Cumulative intensity for 1954-1970 increased by 25% and for 1985-1992 by 14%.

Intensities greater than 25 occur in less than 10% of storms at Kay Point. These storms are responsible for about 50% or more of the cumulative intensities experienced at this site. However, this is not reflected in the correlation between TVLL and cumulative intensity. This may simply be a result of the increased probability of a large storm over longer time intervals, such that intervals with larger cumulative intensity may contain large magnitude storms whereas shorter periods are less likely to do so. Alternatively, it may be that many small storms are as effective in the long term as one or two large storms. The maximum storm intensity on record (with a value of 80) occurred within the longest interval (1954-1970), adding some credence to the first interpretation, but we have insufficient data to come to a firm conclusion. Furthermore, a plot of TVLL in relation to maximum storm intensity shows a close correspondence with a lag of up to 2 years (Fig. 31). This relation produced the highest correlation (R = 0.96; Table 10).

ESTIMATING CLIMATE-CHANGE IMPACTS ON COASTAL RECESSION

Estimates of the impacts of a doubling of pre-industrial levels of CO_2 concentration on the sea ice regime and wave climate of the Beaufort sea have been made by McGillivray et al. (1993). These predictions, based on three different climate models, suggest that the open-water season would increase from 60 to 150 days. Increased open-water fetch distances would result in a 22% to 39% increase in deepwater wave height over a base climate. These estimates assume no change in storm frequency or intensity under a warm climate. Recent work by Lambert (submitted) suggest that there is a small decrease in storm frequency (4%) and a small increase in storm strength for the largest storms under a warmer climate based on the most recent Canadian GCM model results. These changes are not considered significant in this study and no change in storm frequency or strength was assumed under a warmer climate.

Predictions of coastal recession at Tuktoyaktuk

As a starting point, we use the average storm wave height over the period of record (2.1 m) for which effective fetch was non-zero. With the projected increase in wave height of 22-39%, we calculate a new annual storm-average H_s of 2.6-2.9 m. Annual storm duration is a function of the number of storms per year and the duration of the storms. The average storm duration during the period of record was 13 hours and the average number of storms with non-zero fetch was 4. If we assume that storm frequency remains constant throughout the open water season and the projected increase in the open water period is 250%, then an average of 10 storms will occur during the open water season with a total duration of 130 hours (mean duration 13 hours). Substitution of these values into the calculation for annual storm intensity as defined for this study (sum of the product of storm duration and wave height) yields a predicted annual total of 338-377 storm intensity units. This is slightly less than the maximum calculated annual storm intensity during the period of record (387), which occured in 1981, when the highest recorded TVLL also occurred.

Substitution into the regression equations above results in predictions of AVLL which range from 9400 m^3 in the Flagpole zone to less than 1000 m^3 in the North Town zone. TVLL for all zones approaches 15,000 m^3. As mentioned above, these equations take no account of processes related to thaw subsidence or other factors. However, a 250% increase in the duration of open water will greatly increase the thaw rate for permafrost and massive ice, resulting in a probable decrease in any lag effects related to thaw consolidation. The recession might therefore tend to be less episodic.

The predictions are similar (within a factor of 2) to the measured land loss associated with years of severe storm intensity. This suggests that years such as 1981 or 1987 may become more common in the future. Beyond uncertainties in the predictive value of the regression equations, we really have very little information about predicted storm frequency and duration or wind velocity and direction. We have assumed that there will be little change other than an increase in significant deepwater wave height of of up to 39% and an increase in the total number of storms per open-water season. We have also assumed that the proportion of fetch-limited storms during the open-water season will remain constant.

Predictions of coastal recession at Kay Point

The approach taken here is similar to that taken for the Tuktoyaktuk dataset. The increase in total duration is based on the assumption that storm frequency remains constant and the open water season increases by 250%. Storm wave height is predicted to increase by about 22-39%. The number of storms with non-zero fetch will increase from 3 to 8 with a total duration of 112 hours; storm wave heights will increase from the presently calculated value of 1.3 m to between 1.6-1.8 m. Thus the predicted annual storm intensity will increase to 180-202 from present values of about 50-60 and a maximum annual cumulative intensity of 149 which occurred in 1960. The predicted VLL for the predicted average annual intensity, based on the TVLL/Cumulative linear regression equation is about 90,000 m^3/a. This is roughly two times the highest historical rates and similar to the two year maximum which occurred in 1970 to 1972.

It is important to remember that the coastal erosion database for Kay Point is based on 2 to 16 year averages. Any lag effects of the type described at Tuktoyaktuk may have been averaged out. In addition, the suggestion that changing Mackenzie River Discharge may affect ice edge position and effective fetch at Kay Point has not been evaluated.

Comparison between Tuktoyaktuk and Kay Point

TVLL at the two sites cannot be compared directly because the measurements are based on a particular length of coastline. By dividing the TVLL by the length of the segment we arrive at a figure for comparison which only reflects cliff height and recession. The total length of the Kay Point segment is 1750 m, therefore the predicted cliff erosion is 90,000 m^3 divided by 1750 m, or 51 m^3m^{-1} of coastline. Predicted overall erosion at Tuktoyaktuk (15,000 m^3) was spread out over a 900 m segment, so its erosion rate per unit of time is 17 m^3m^{-1}. The predicted rate at Flagpole is close to 30 m^3m^{-1}. Similarly, the regression equations can be directly compared by dividing the slope and the intercept by the length of the coastline under investigation. The slope of the Kay Point equation is 0.14 m^3m^{-1} per SI unit and that of the Tuktoyaktuk equation is 0.06 m^3m^{-1} per SI unit (about 0.10 at Flagpole). Thus, for these two eroding sections of both the Yukon and the Tuktoyaktuk Peninsula coasts, cliff recession will increase at a rate of about 0.6 to 1.4 m^3m^{-1} for every 10 unit increase in annual storm intensity (or about every 5 additional storm hours at typical predicted storm wave heights).

The similarity in the volume of eroded material per metre of coast between the two sites is intriguing, especially given the much higher intensity levels found on the Tuktoyaktuk coast. Although cliff heights at Kay Point and Tuktoyaktuk are comparable, at least for the Flagpole zone at Tuktoyaktuk, the similarity may simply be coincidental. Alternatively, it could suggest that erosion is self-limiting at the time scale of storm events. This was alluded to in the section dealing with lags in erosion rate at Tuktoyaktuk, where storm-induced erosion encounters ice and permafrost after removing thawed material. The frozen material is more difficult to erode and appears to limit erosion over the short term (individual storm events or series of events). If this is the case, then increasing energy levels in a single season may not produce the predicted increase in erosion. However, more frequent high intensity storm years coupled with long open-water seasons with enhanced coastal melting rates will increase erosion rates over several seasons.

CONCLUSIONS AND CAVEATS

This study has demonstrated a strong correlation between measured coastal recession and an index of storm intensity at two sites on the Beaufort Sea coast.

These sites are among the most rapidly retreating parts of the coastline. The results presented here are therefore biased to conditions favouring rapid erosion. It is not clear to what extent they may apply to more slowly retreating areas, though some of the more stable zones at Tuktoyaktuk may be taken as representative of sites experiencing slower recession.

It should be noted that empirical relations of the kind developed here cannot reliably be extended to other sites or to conditions outside the domain of the source data. Furthermore, these relations clearly cannot predict the outcome if system thresholds are exceeded and response characteristics change (e.g. because of changes in temperature or other parameters that may result from a secular change in climate). The predictions of increased erosion rates resulting from doubled CO_2 are persuasive but must be treated with caution. While it is difficult to apply the regression equations to other areas of the Beaufort Sea coast, the similarity in predicted volumes of material eroded per unit of coastline may provide a rule of thumb if applied judiciously to sites with similar features (e.g. similar geology, orientation, exposure, shoreface slope, etc.). The data in this report can also be used to assist in the development of deterministic models of coastal response to climate change based on physical principles. In particular, the Tuktoyaktuk database can be used to calibrate coupled thermo-erosion and sediment transport models, which can then be applied to other parts of the Beaufort Sea coast. Previous attempts (e.g. Pinchin et al., 1985) have been based on southern models of sediment transport without incorporating thermal factors and their results were therefore ambiguous.

The results of this study provide a rational basis for assessing potential effects of climate change along the coast and for planning appropriate responses. They indicate a probable acceleration in coastal erosion under conditions of diminished sea-ice extent and duration, with or without a comcomitant increase in storm frequency or severity. It is common practice in areas of coastal erosion hazard to plan setback of new construction so as to ensure a reasonable life expectancy for the installation or structure. Setback is commonly established on the basis of existing coastal recession rates and a specified duration such as 50 or 100 years. This study demonstrates that, within a 50- to 100-year time frame, climate change may cause an acceleration of coastal recession, necessitating a revised procedure for determining appropriate setback. Despite the shortcomings of our empirical results, they provide a better means of predicting the required setback than recession estimates derived solely from existing erosion data.

Climate change may be manifested in numerous ways and include a variety of complex interactions. In addition to the changes in sea-ice distribution and wave climate discussed above, we may anticipate related changes in storm characteristics, storm water levels, air and water temperature, precipitation, and runoff (including changes in Mackenzie River discharge and freshwater inflow to the Beaufort Sea). Changes in mean sea level are also expected. The effects of rising sea level on coastal stability have attracted considerable attention in other parts of the country (cf. Forbes et al., 1989; Clague, 1989; Shaw et al., in press) and a compilation of coastal susceptibility to sea-level change throughout Canada is being prepared by the Geological Survey. In the Beaufort Sea, relative sea level is thought to be rising now at a rate of less than 3 mm a^{-1} (Forbes, 1980, 1989; Hill et al., 1993), but difficulties maintaining vertical control on the tide-gauge data, the short length of the record (about 30 years), and high variance of water levels make it difficult to determine the rate unequivocally. Expected global changes in sea level over the next 50 to 100 years may more than double the rate of relative sea-level rise in the Beaufort Sea, increasing the rate of transgression on low-lying tundra and delta coasts and raising the level of storm-wave attack on other shorelines. These changes are expected to complement and reinforce the wave climate changes discussed above, but a quantitative assessment of coastal response to sea-level rise in the Beaufort Sea is beyond the scope of this study.

In a wide-ranging statistical assessment of factors affecting coastal stability on the Tuktoyaktuk Peninsula coast, Héquette and Barnes (1990) concluded that variations in wave energy were of minor importance compared to other factors such as sea-ice interaction on the shoreface. While we do not discount the influence of various other mechanisms, including ice scour, ice entrainment of sediment, thermal degradation and thaw consolidation (see above), our results clearly establish the overriding importance of storm waves (in particular, wave energy and duration, as quantified in the storm intensity index) as the major factor determining the rate of coastal recession at Tuktoyaktuk and Kay Point. This conclusion is consistent with the results of Hume et al. (1972), who found little correlation with temperature or precipitation but a strong dependence on westerly storm incidence in their study of coastal erosion on the Alaskan Beaufort Sea coast.

In summary,

(1) Using storms defined on the basis of wind speed greater than 37 km h^{-1} (20 knots or 10 m s^{-1}) and duration greater than 6 hours, a storm intensity index was developed that incorporates ice-free fetch, hindcast deepwater significant wave height, and duration of the event.

(2) Using this storm index, coastal sites at Tuktoyaktuk, North Head, and Tent Island were found to have experienced strong variations in storm intensity over the past 33 years, with greater storminess in the early to mid-1960s and in the 1980s and a quiet interval from the late 1960s through the 1970s. Kay Point, on the central Yukon coast and closer to the summer ice edge, displayed less variation in storm intensity throughout the period of record.

(3) A strong correlation has been demonstrated between storm intensity and coastal recession where sufficiently detailed time series of erosion rates are available (Tuktoyaktuk and Kay Point).

(4) Although wave energy clearly constitutes the dominant control on coastal recession rates, a number of other factors play important roles, in particular permafrost and ground ice with associated thaw processes. The relative importance of sea-ice scour and sediment entrainment during freezing storms remains to be established.

(5) The empirical models developed in this study can be used at the sites where they were developed to provide a broad indication of the magnitude of erosion to be expected under various climate change scenarios involving changes in storm frequency and severity and in the distribution and extent of sea ice.

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CONCEPTUAL MODEL OF LINKAGES

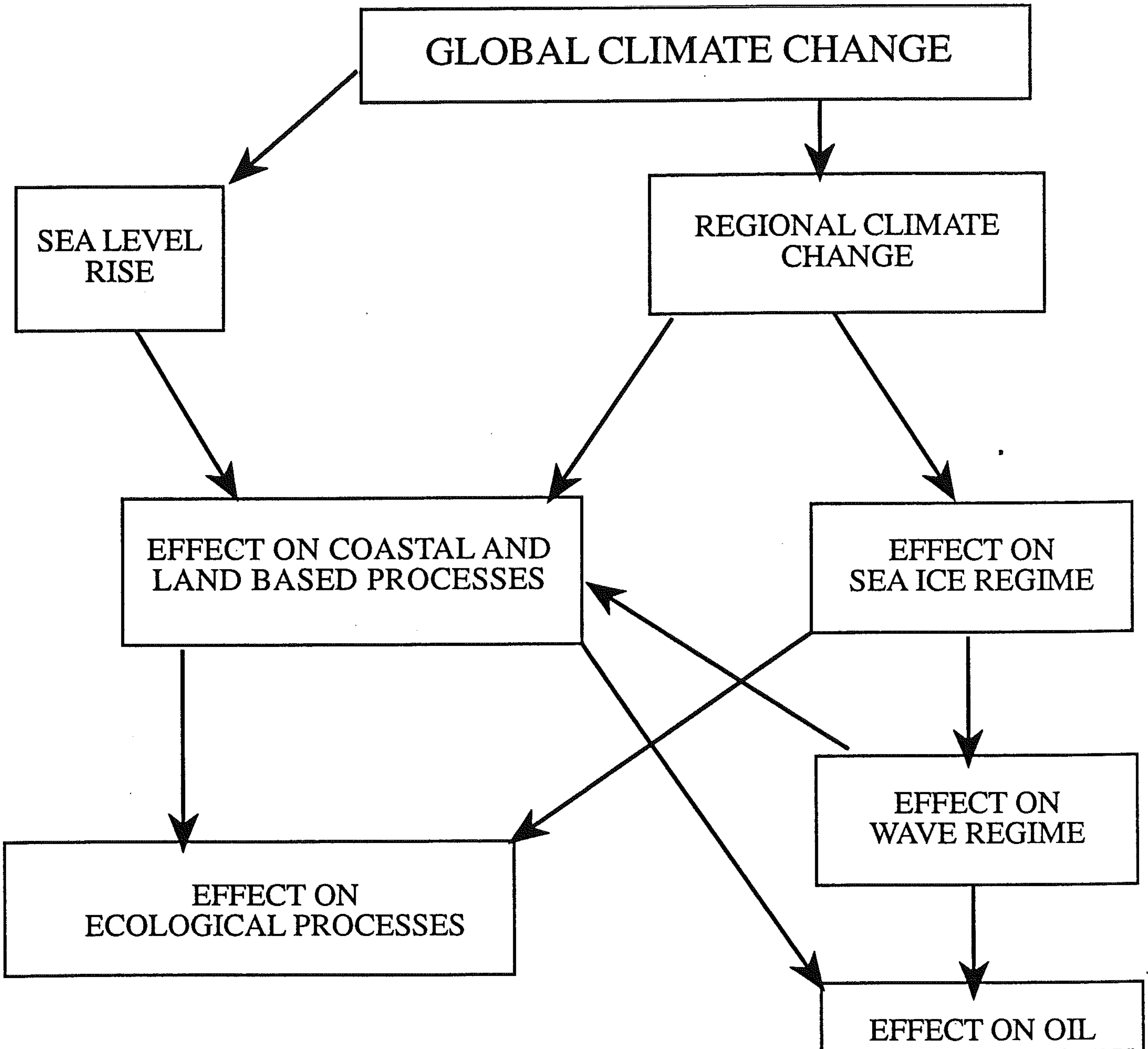

Figure 1: Conceptual model of linkages between climate change processes, the sea-ice regime, and activities of the Arctic Petroleum Industry. Similar diagrams can be constructed for impacts on communities, parks, etc. (Modified after Macgillivray et al, 1993)

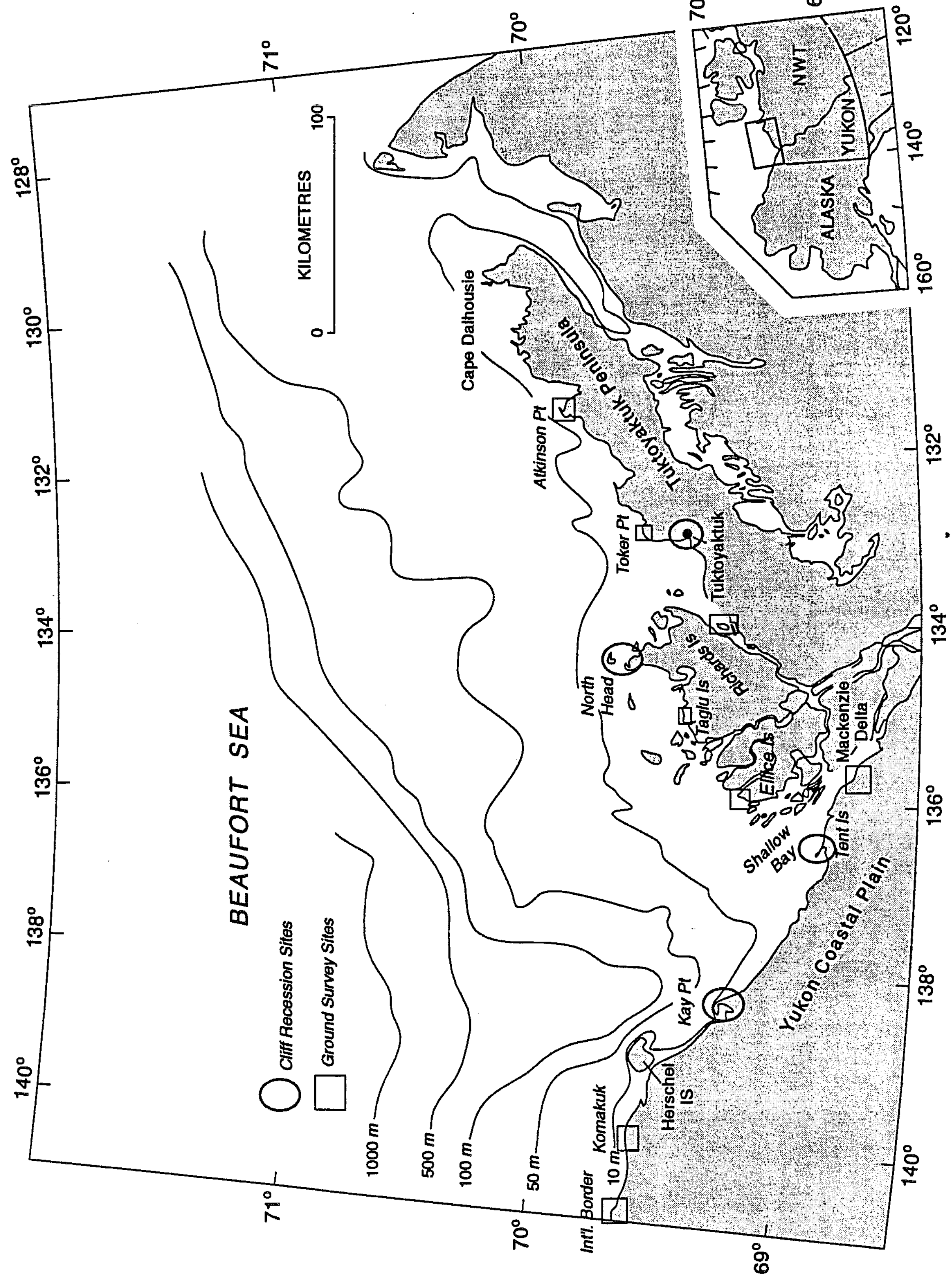

Figure 2 Canadian Beaufort Sea coast, showing erosion monitoring sites. Circles delineate detailed study sites described in this report, Boxes are ground survey sites.

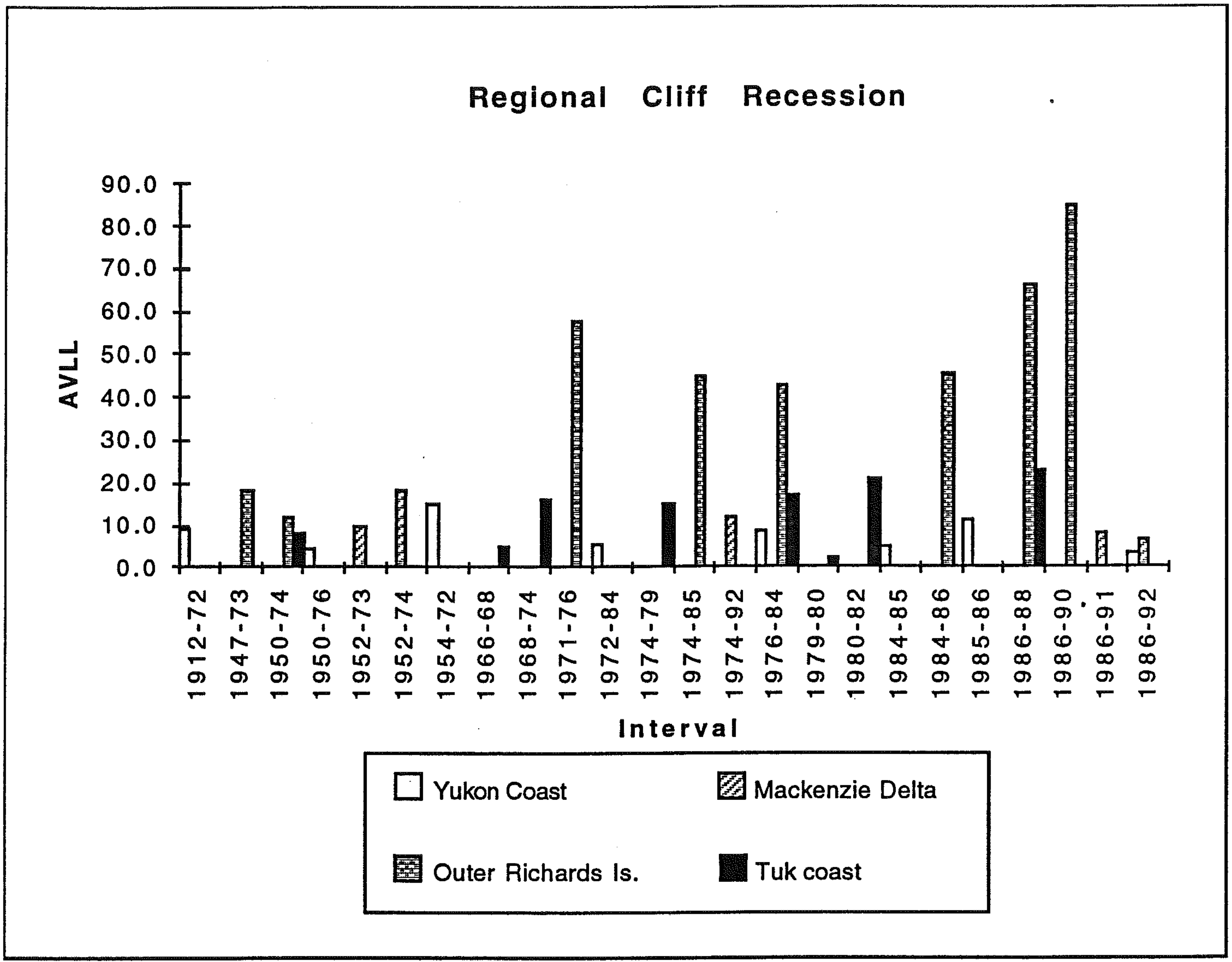

Figure 3 Annual Volumetric Land Loss (AVLL) (m^3a^{-1}) along the Canadian Beaufort Sea coast, at a range of sites from various published sources, classified by time interval and geographic region. Data for 1912-1972 and post-1970 time intervals are from gound surveys. Other results are from air photo analyses by various methods (see text).

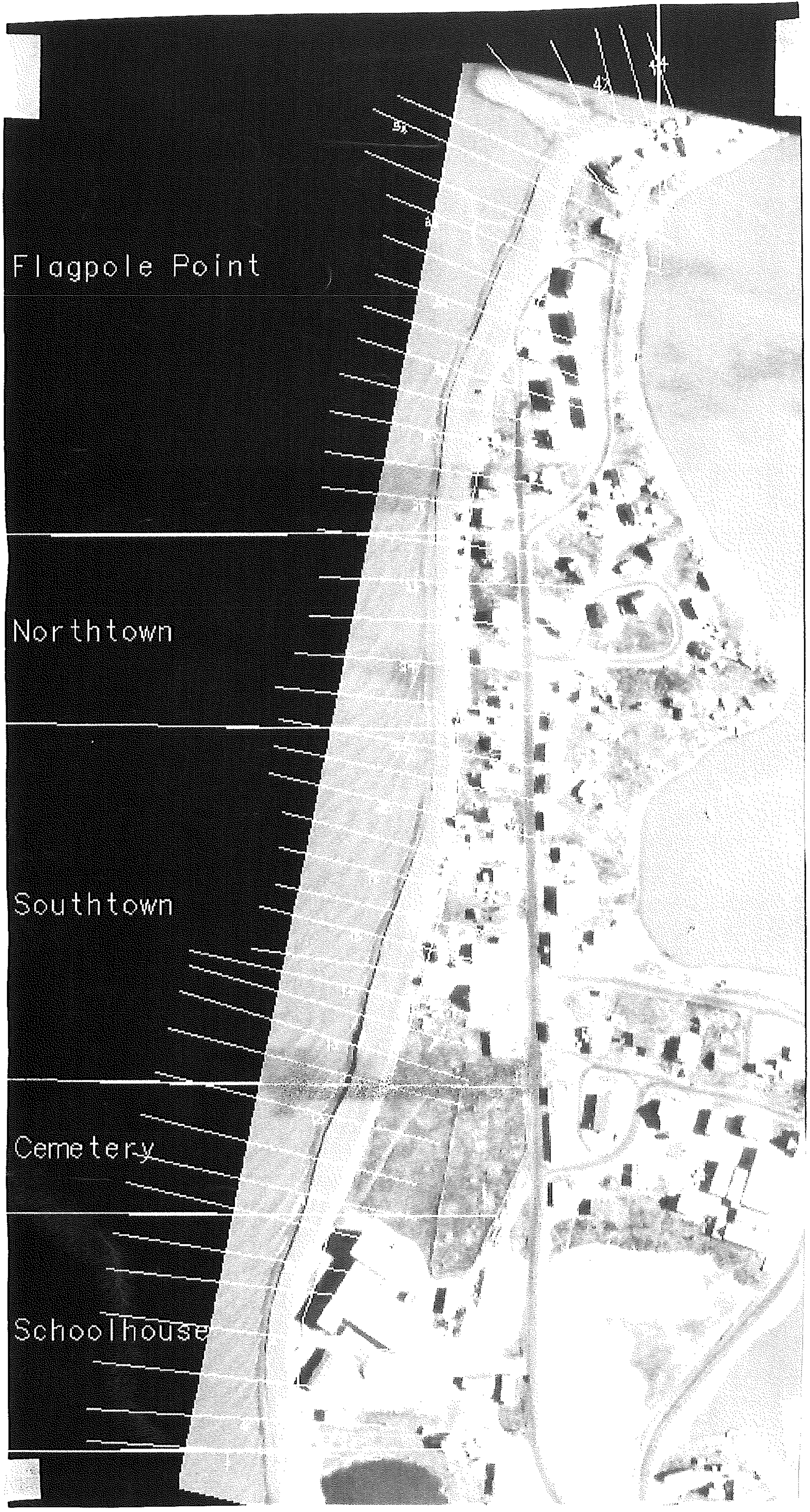

Figure 4 Air photograph of the Hamlet of Tuktoyaktuk showing the alongshore divisions used for cliff recession measurements and the shore orthogonals along which recession was measured at 20 m intervals.


E-F
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38

Figure 5 Air photo of the North Head shoreline. The letters designate the alongshore zonation used for area measurements and the numbered lines are the shore orthogonals along which linear recession was measured at 110 m intervals.


4
6
8
10
12
14
2
1

Figure 6 Air photo of the Tent Island shoreline . Measurement of linear erosion took place along shore orthogonals spaced 100 m apart. The area eroded was measured between the most easterly and westerly orthogonals.

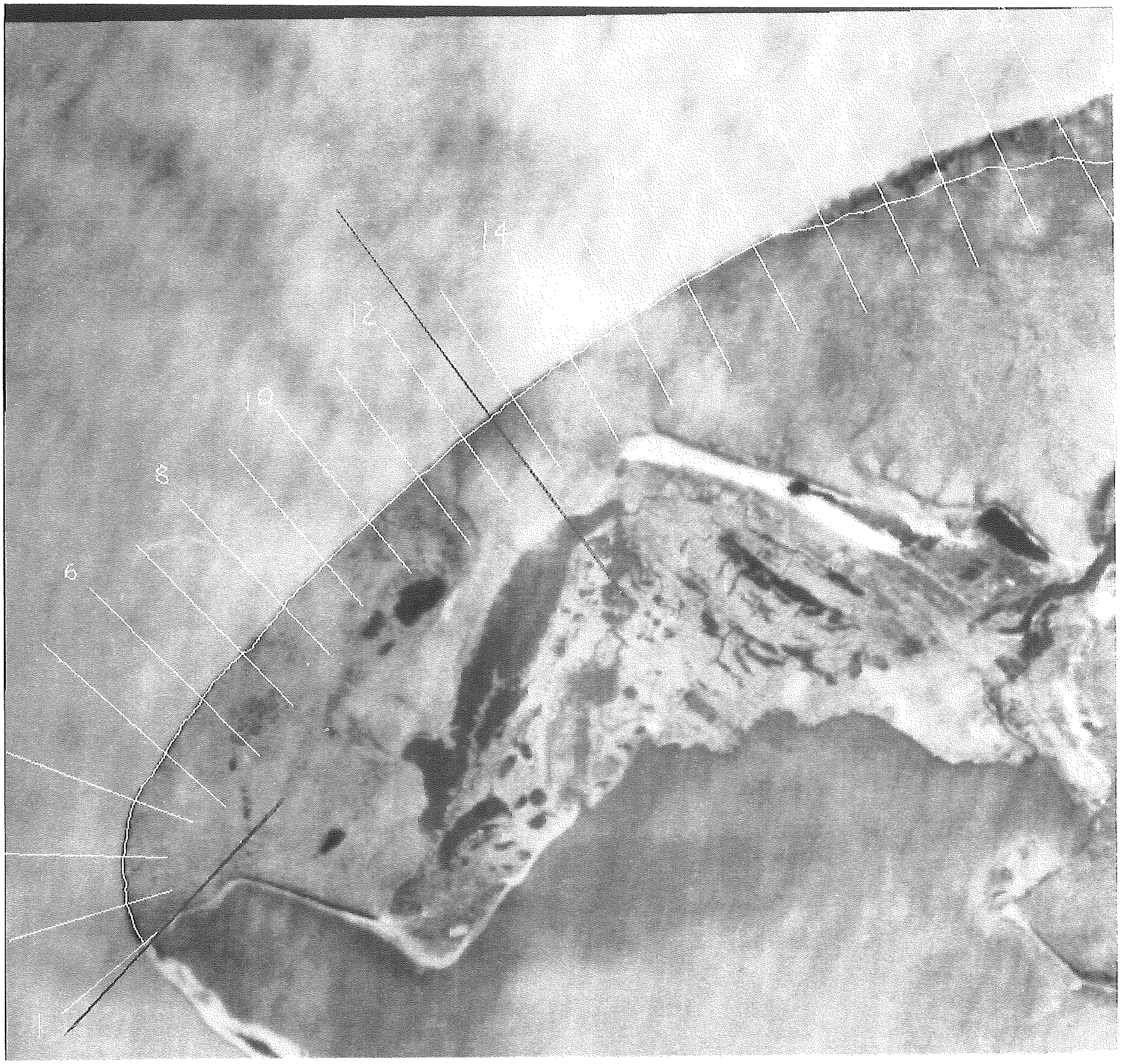


Figure 7 Air photo of the Kay Point shoreline . Measurement of linear erosion took place along shore orthogonals spaced 140 m apart. The area eroded was measured between the first and last orthogonals.

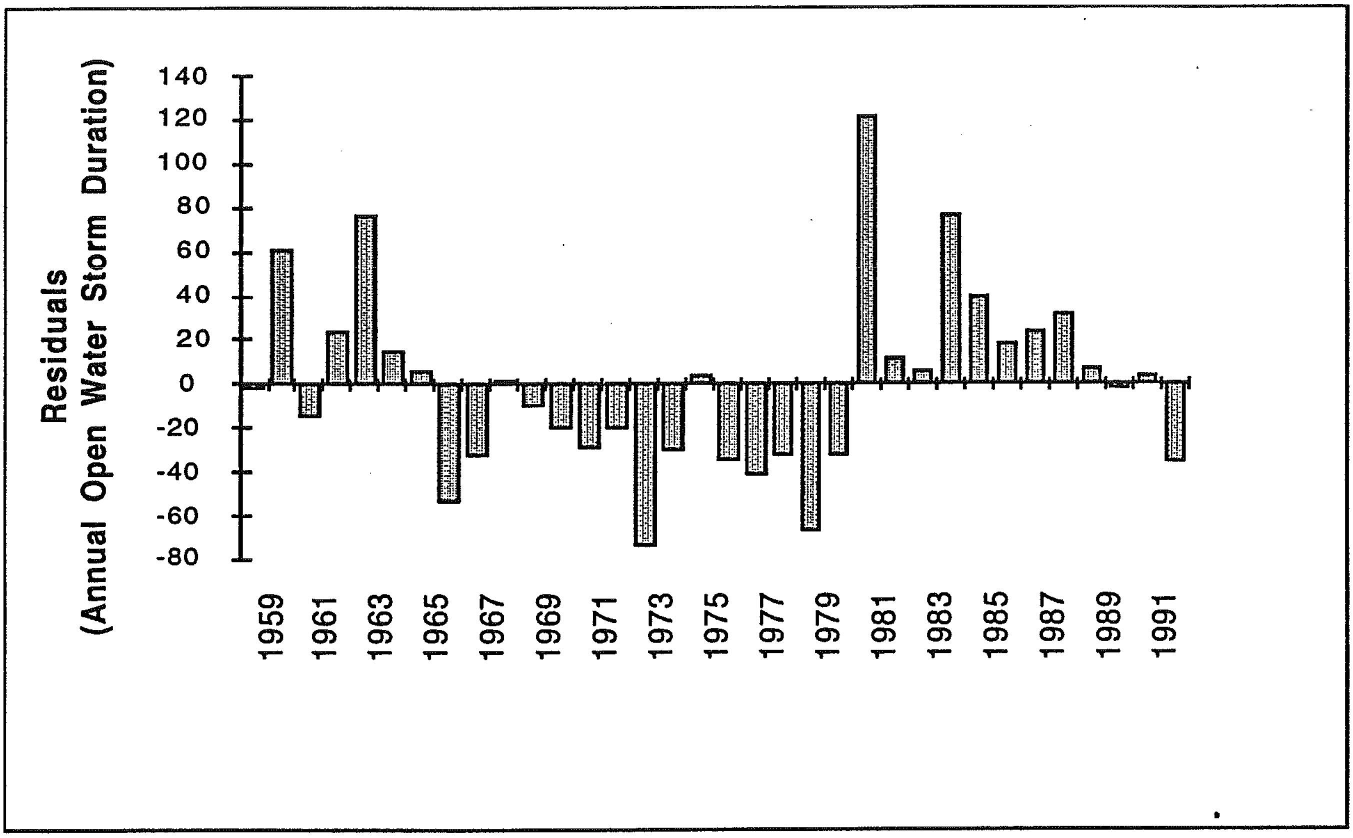


Figure 8 Annual duration (in hours) of storms expressed as deviation from the mean for the 33 years of record.

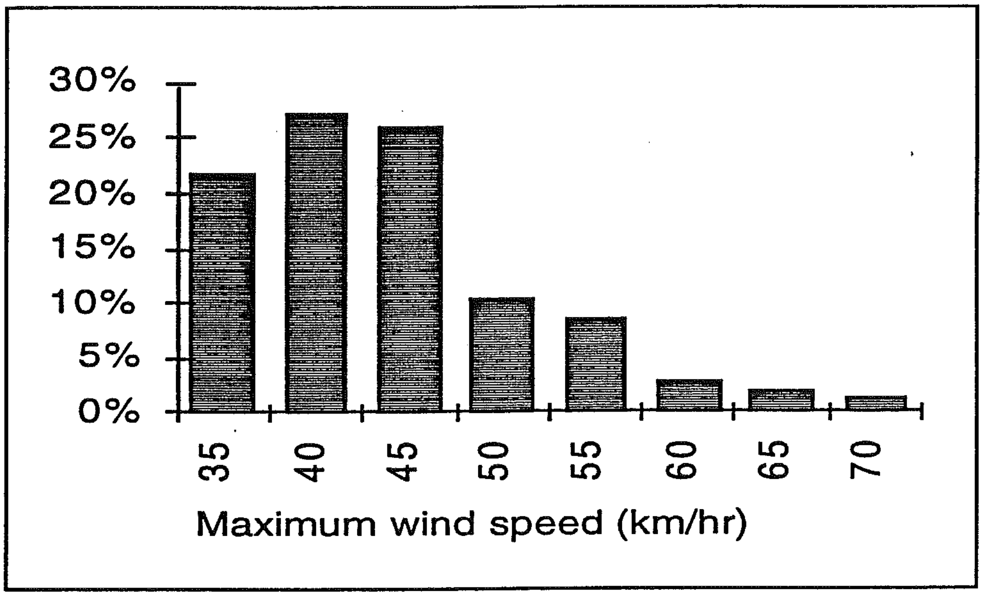


Figure 9 Frequency distribution of maximum wind speed (km/h) during storms (AES data from Tuktoyaktuk DEW-line station).

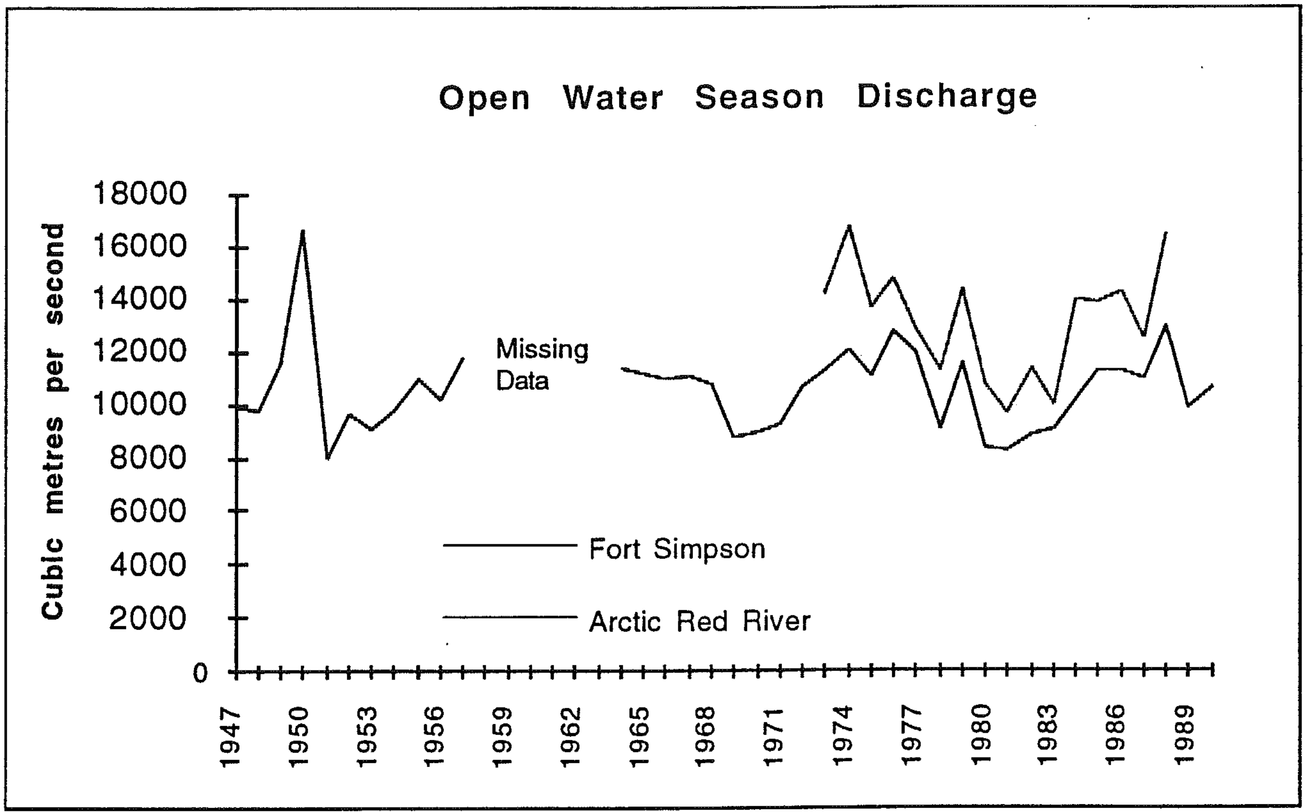


Figure 10 Mean discharge (June-October) in Mackenzie River at Fort Simpson and Mackenzie River above Arctic Red River (data courtesy Inland Waters Directorate, Atmospheric Environment Service).

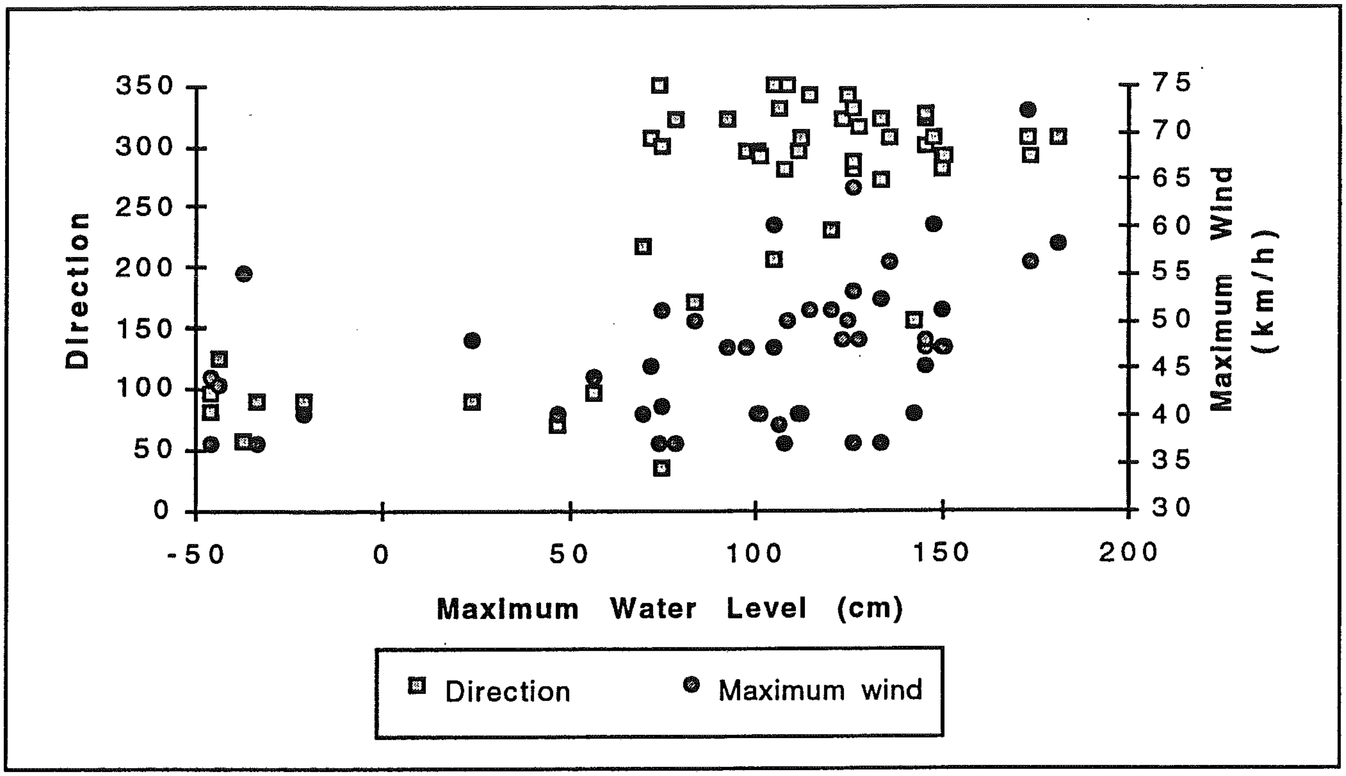


Figure 11 Wind direction and wind speed in relation to water levels recorded at Tuktoyaktuk (wind data from AES; water level data courtesy Marine Environmental Data Service).

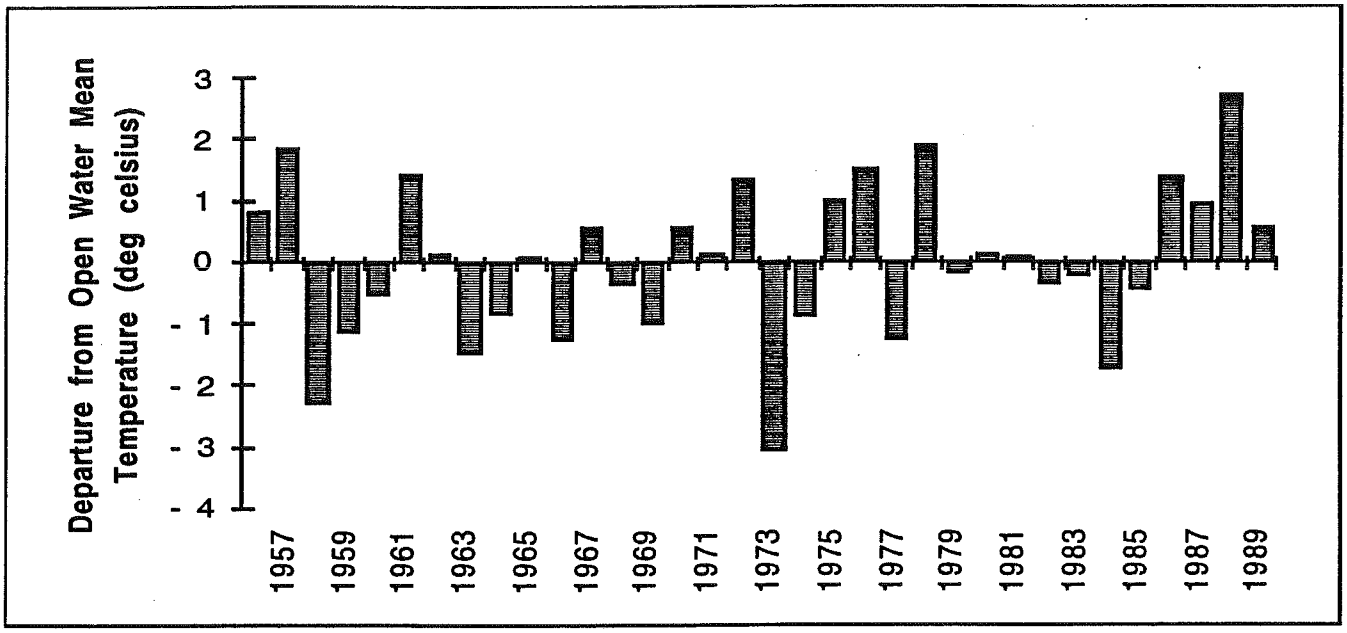


Figure 12 Annual mean air temperature departures from the overall mean for 33 years of record (AES data from Tuktoyaktuk DEW-line station).

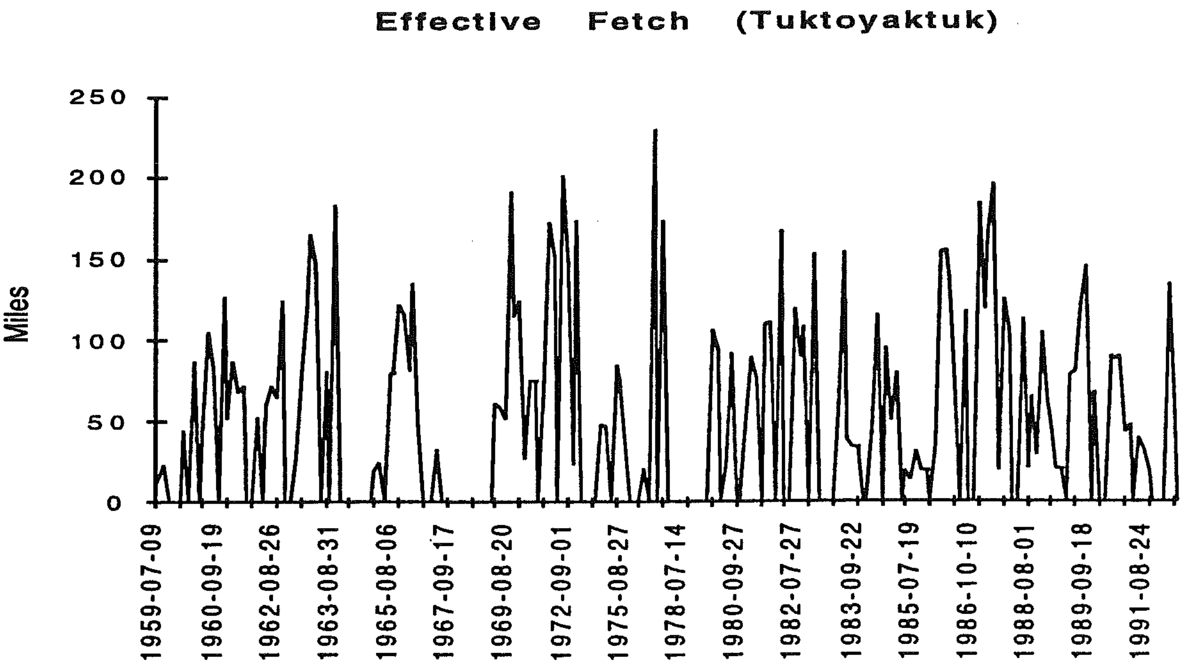


Figure 13 Effective open water fetch at Tuktoyaktuk.

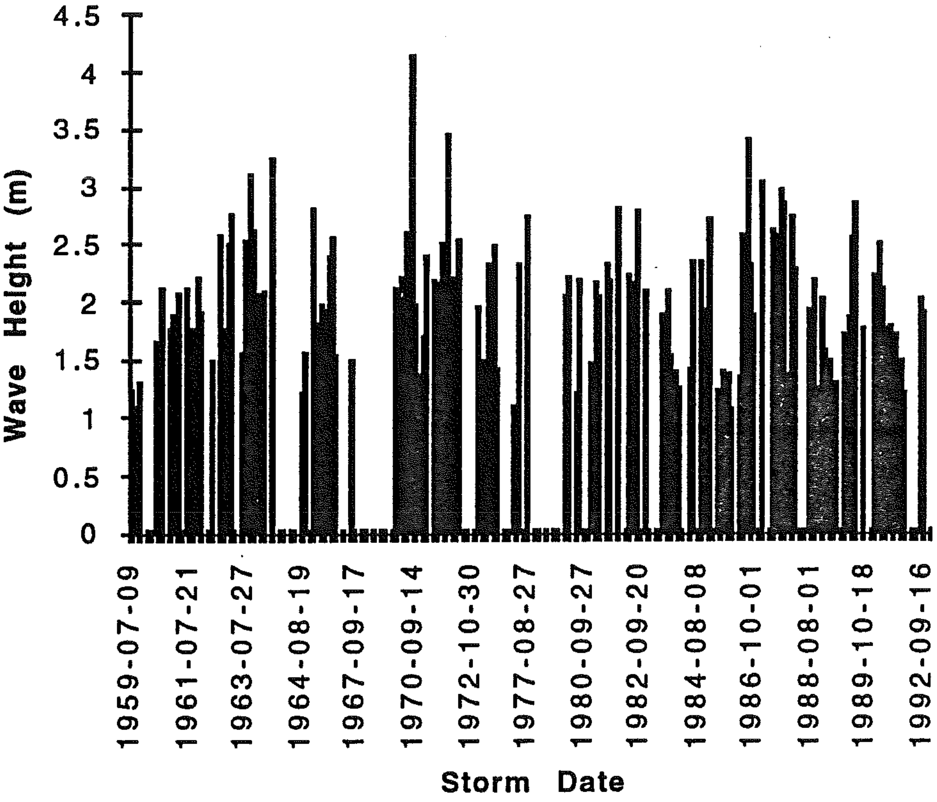


Figure 14 Hindcast deepwater wave height off Tuktoyaktuk for each of the storm events identified in the 33 years of record.

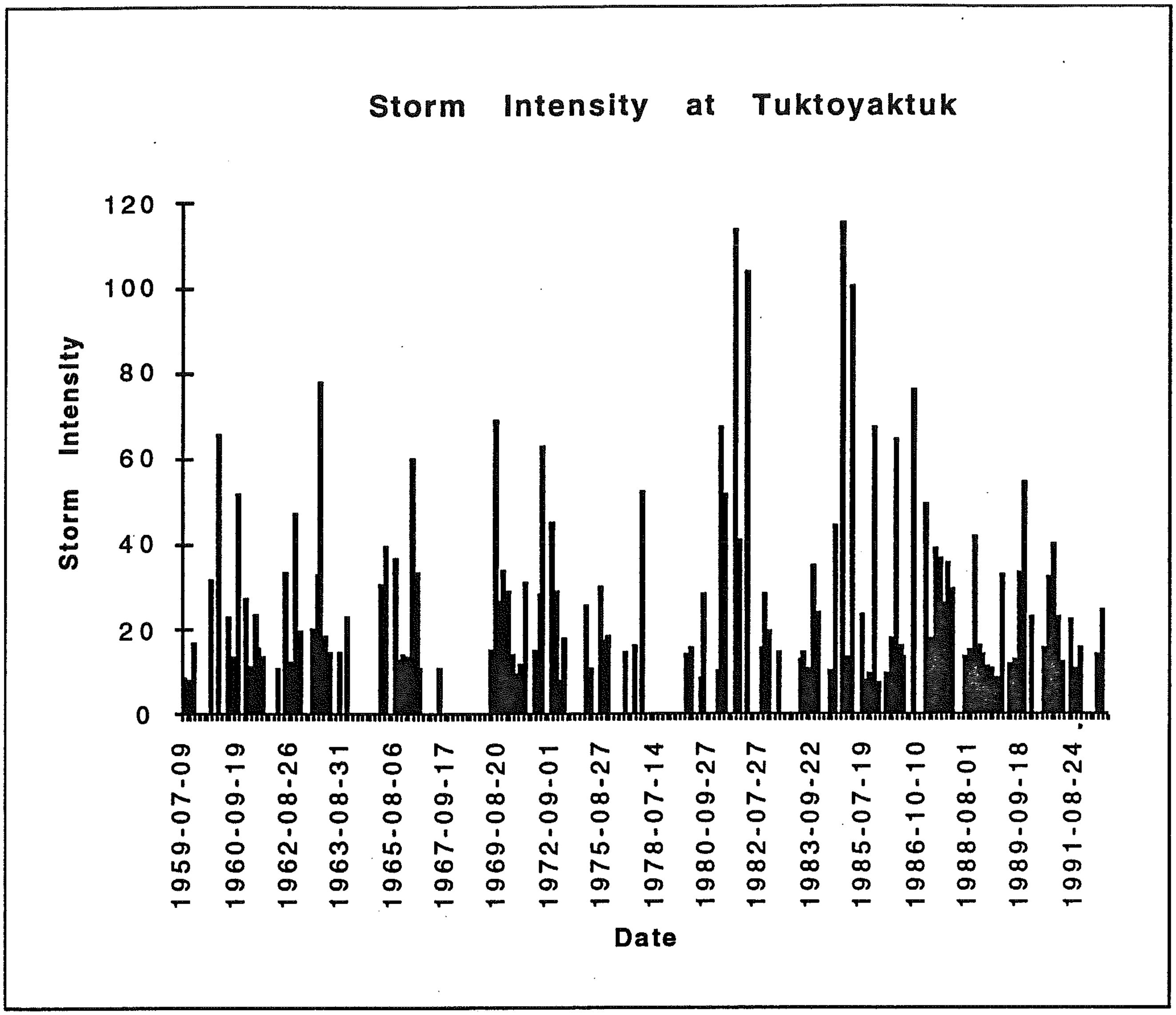


Figure 15 Time series of storm intensity at Tuktoyaktuk. Storm intensity is the product of deep water significant wave height in metres and the storm duration in hours. It is used as an index of storminess. Storm event statistics are listed in Appendix B.

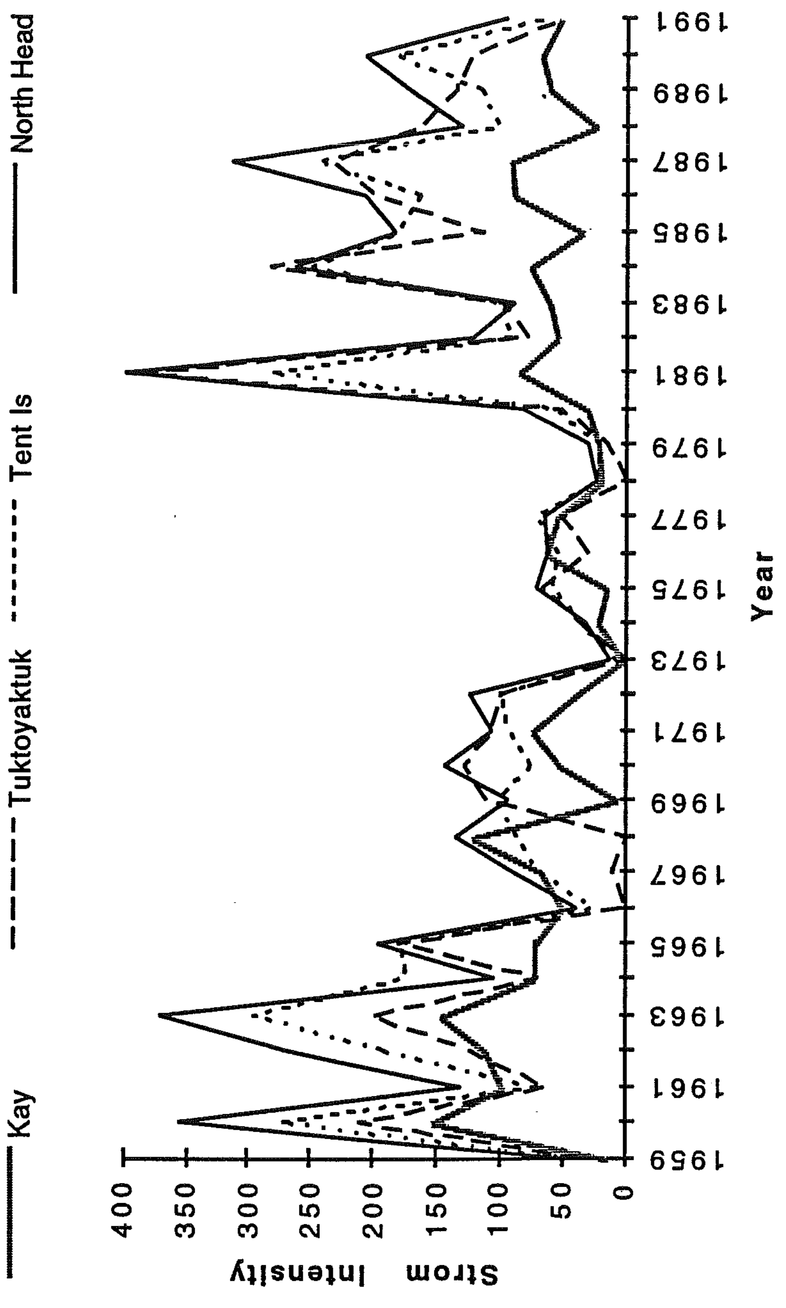


Figure 16 Annual cumulative storm intensity, $\Sigma(H_s \cdot \Sigma t)$, where H_s is hindcast significant wave height and Σt is storm duration, for each of the storm events at Tuktoyaktuk, North Head, Tent Island and Kay Point, showing effects of varying fetch.

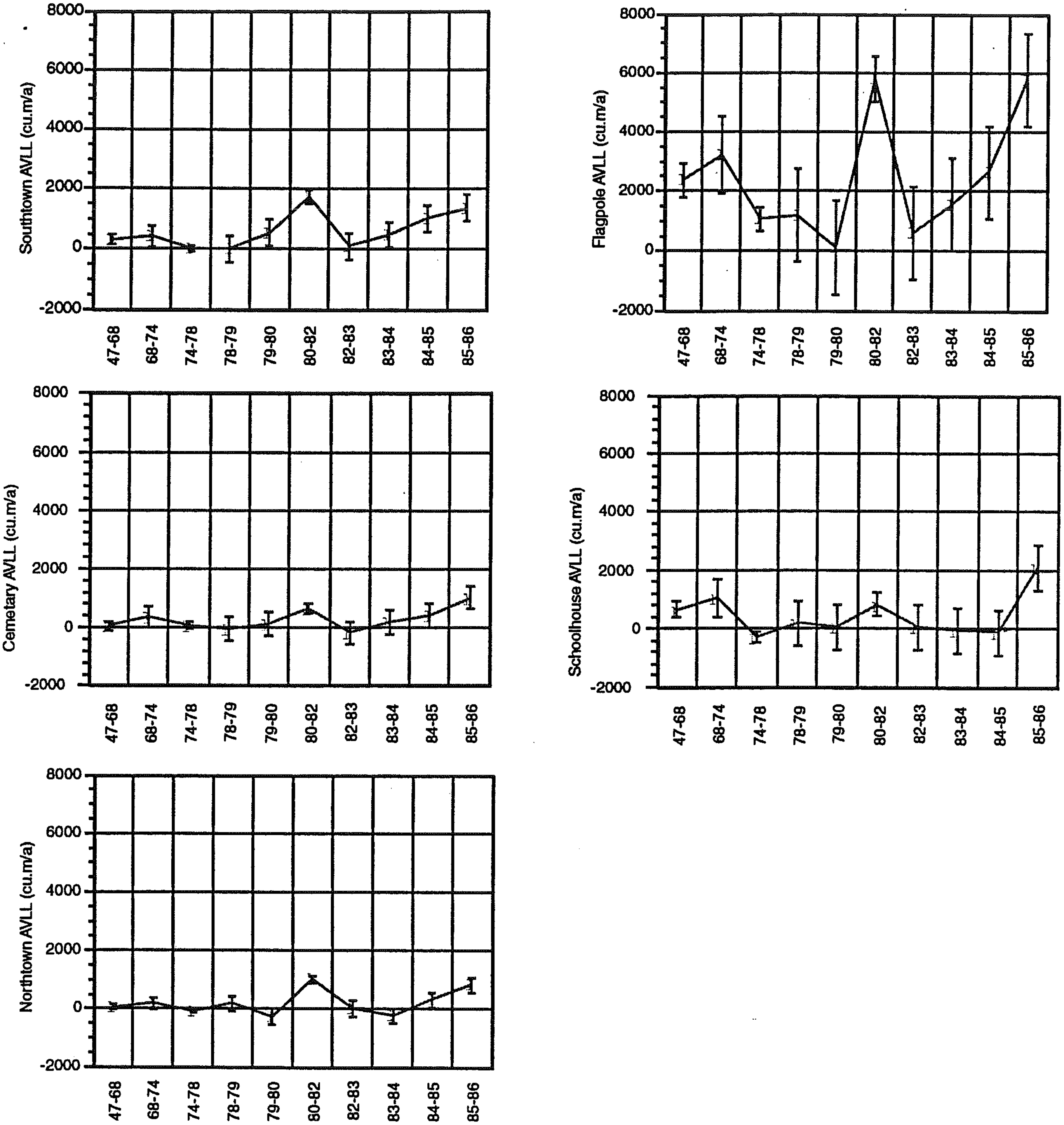


Figure 17 Annual volumetric land loss (AVLL in m^3a^{-1}) at Tuktoyaktuk for each of the five zones depicted in Figure 2.

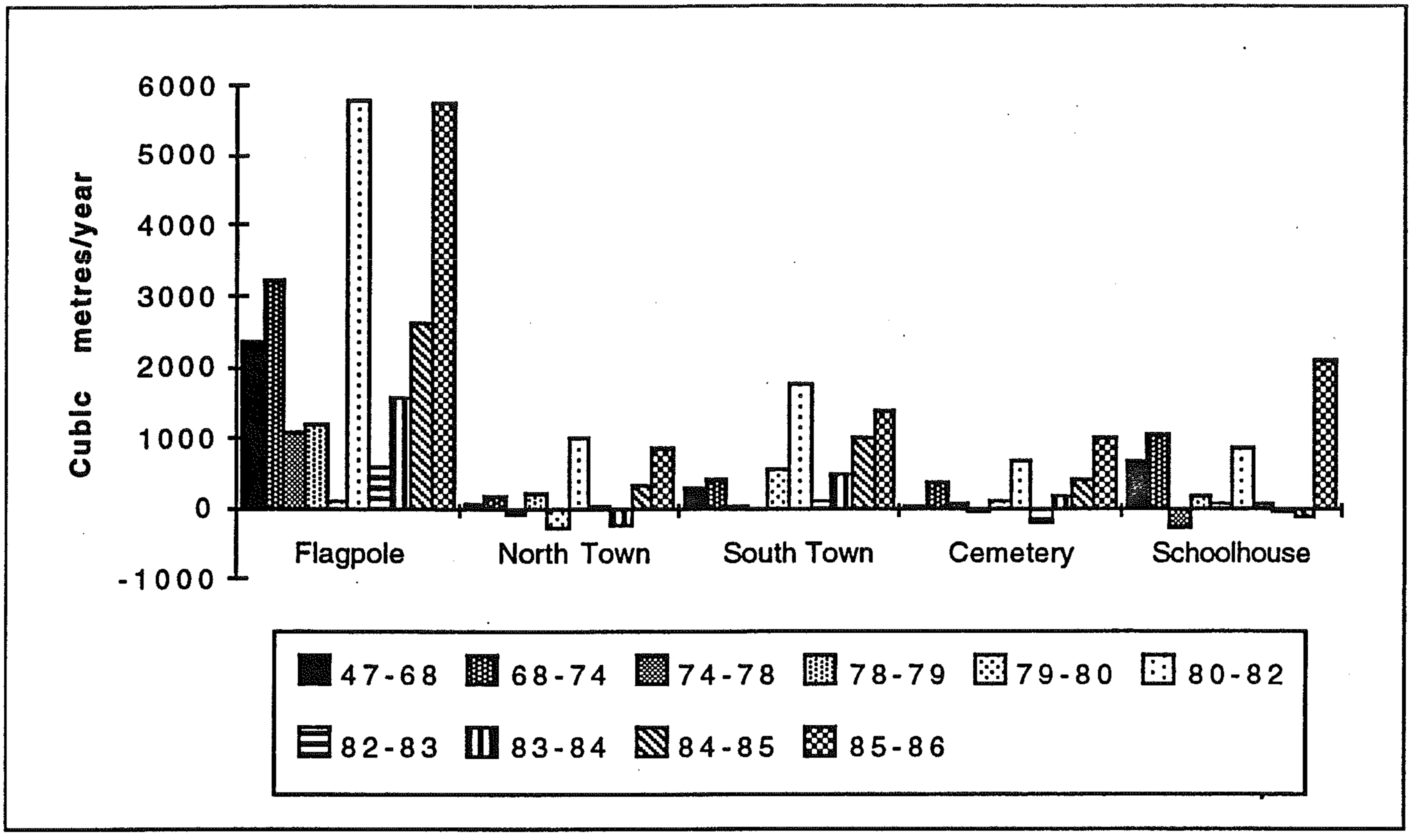


Figure 18 Erosion rates at Tuktoyaktuk, showing variation between zones and through time. The intevals depicted in the legend represent the years between air photography missions (e.g.47-68 represents the time interval from 1947 to 1968).

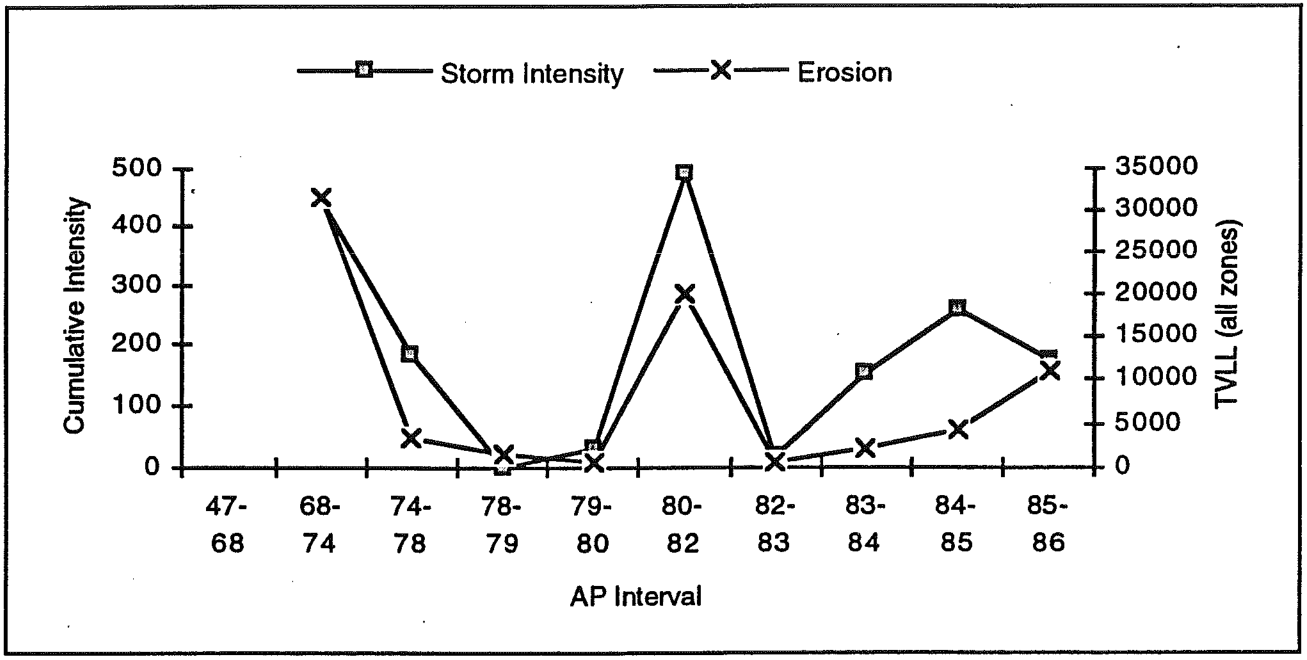


Figure 19 Total Volumetric Land Loss (TVLL) and cumulative storm intensity by air-photo interval (AP interval) at Tuktoyaktuk (1968-1986).

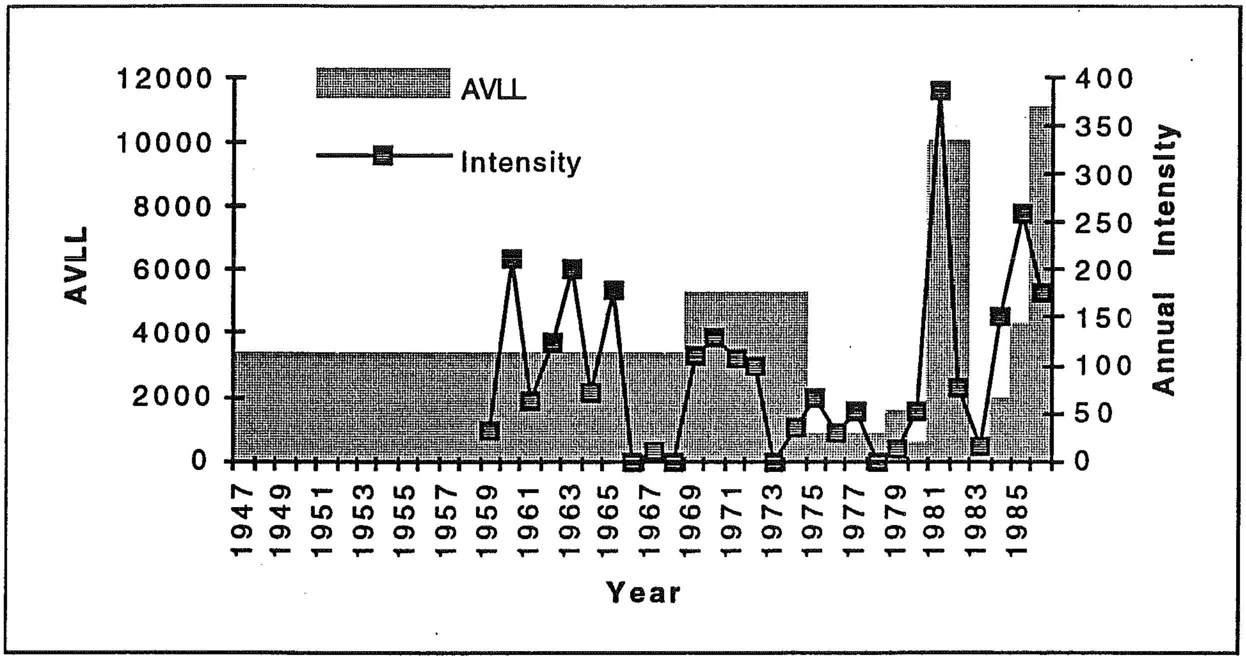


Figure 20 Average annual volumetric land loss (AVLL) at Tuktoyaktuk (1947-1986) in relation to annual storm intensity (1959-1986).

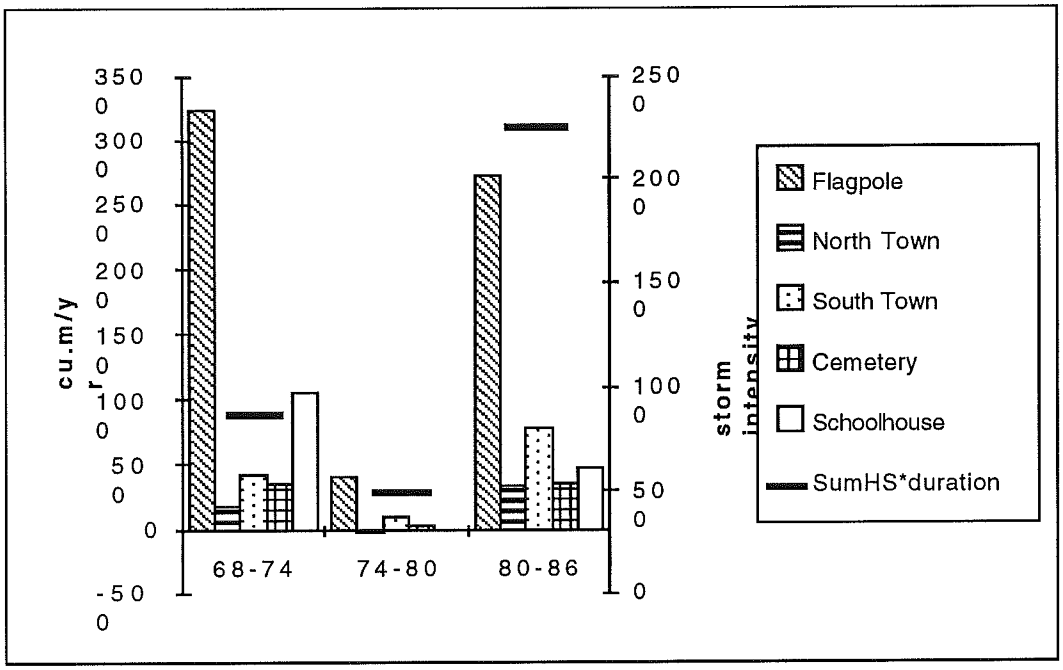


Figure 21 Average erosion by shore zone in relation to mean storm intensity for six-year intervals at Tuktoyaktuk (1968-1986). See Figure 2 for the shore zonation. SumHs*duration represents the average annual storm intensity

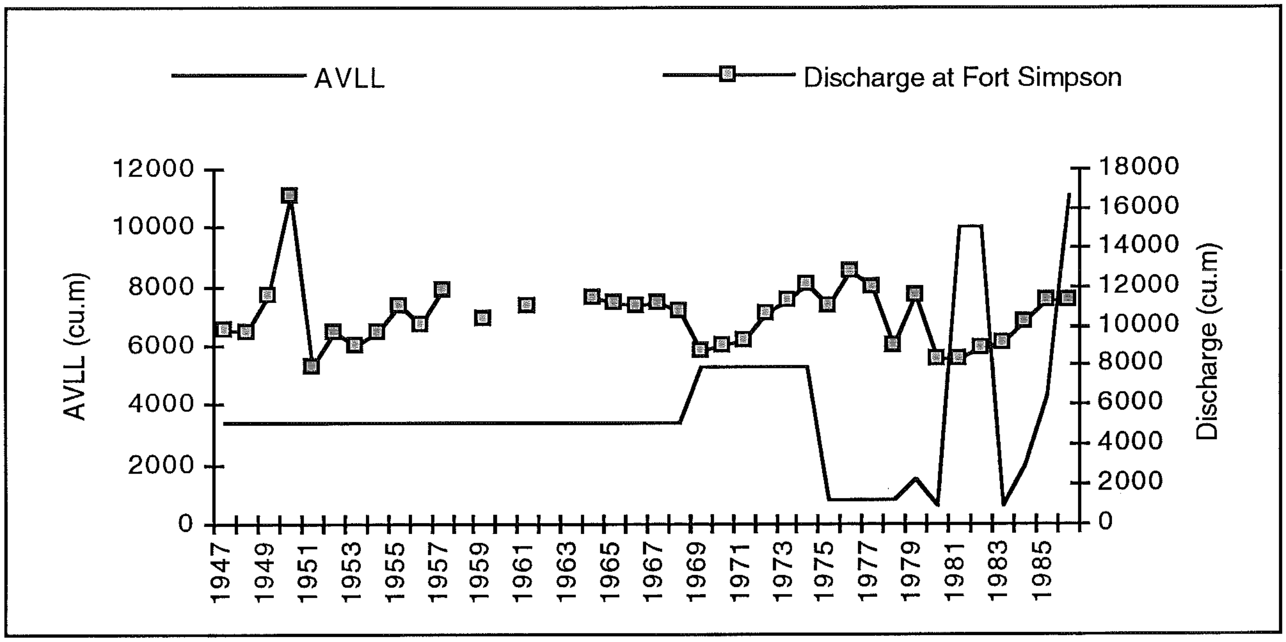


Figure 22 Annual volumetric erosion (AVLL) at Tuktoyaktuk in relation to Mackenzie River discharge at Fort Simpson (1947-1986).

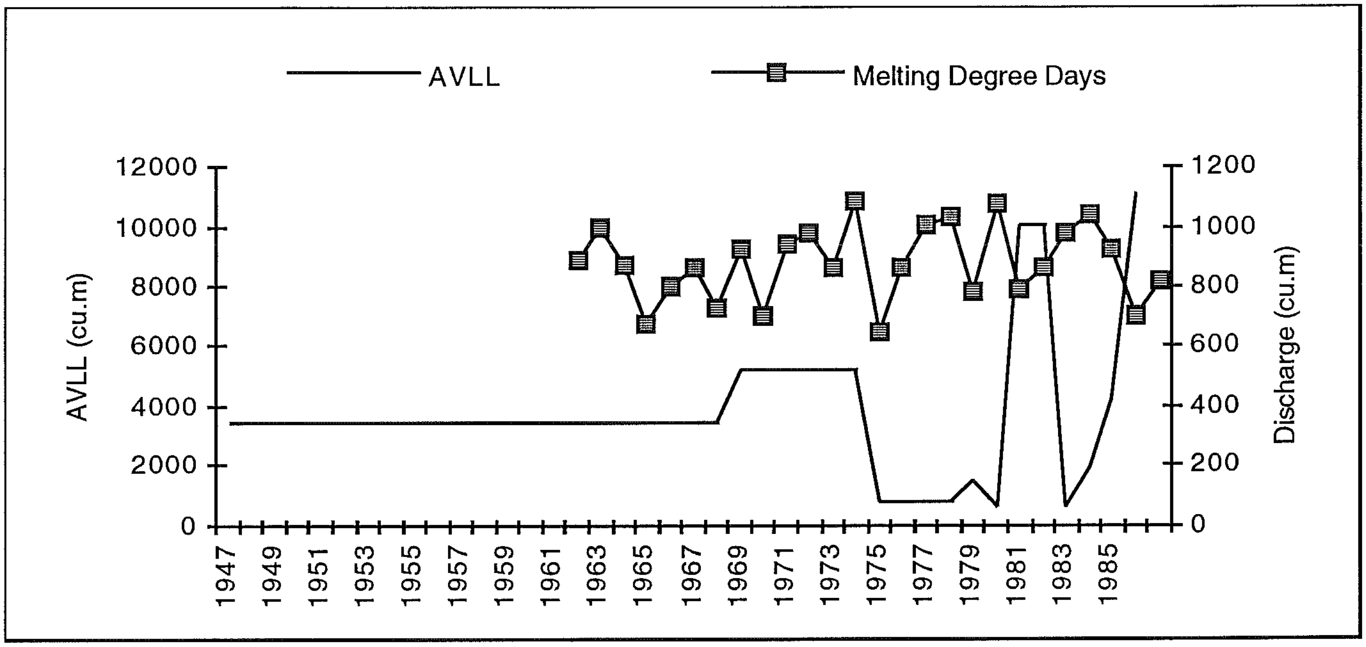
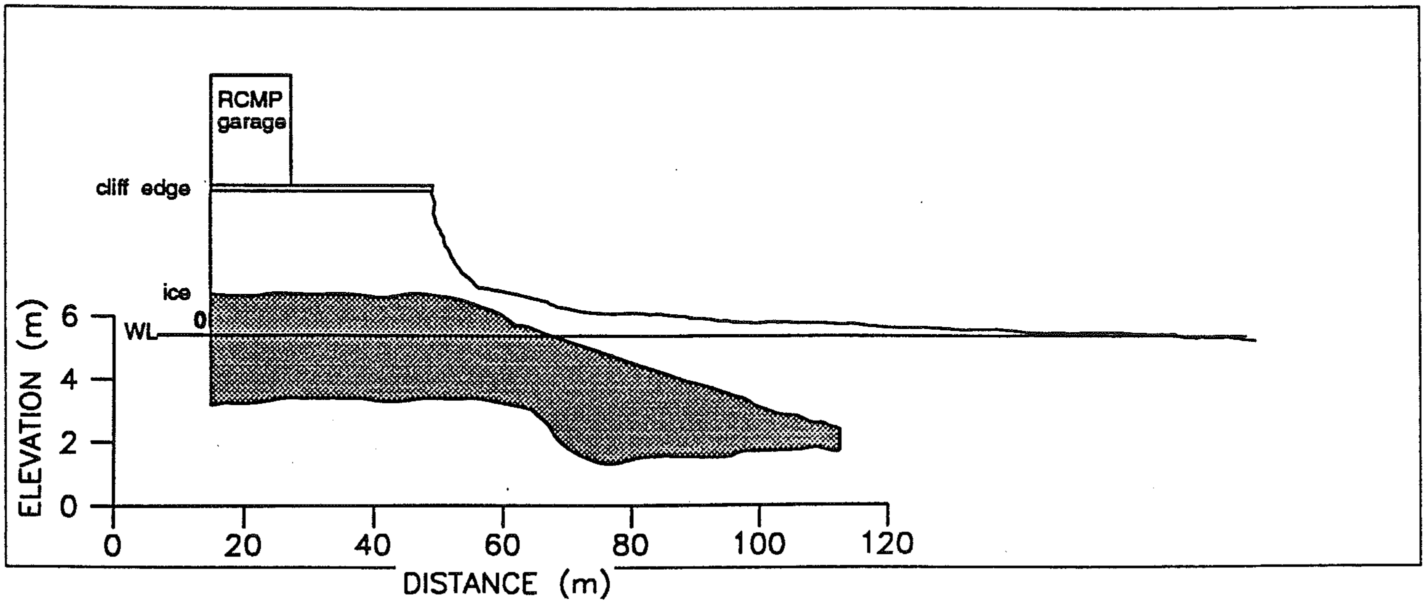


Figure 23 Annual volumetric erosion (AVLL) at Tuktoyaktuk (1947-1986) in relation to annual series of melting-degree-days (1962-1987).

Cliff profile at Flagpole Point, 1975



Cliff profile at Flagpole Point, 1992

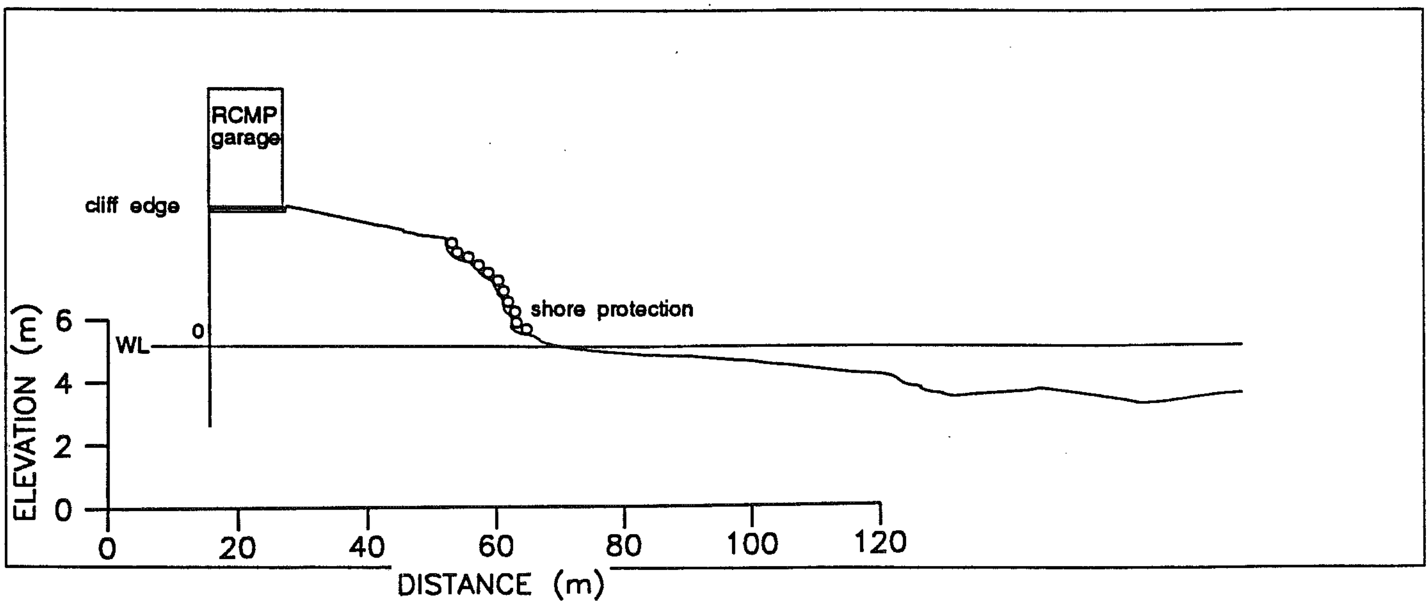


Figure 24 Cross-shore profiles in the Flagpole zone in 1975 (after Kolberg and Shah, 1976) and 1992 (GSC data).

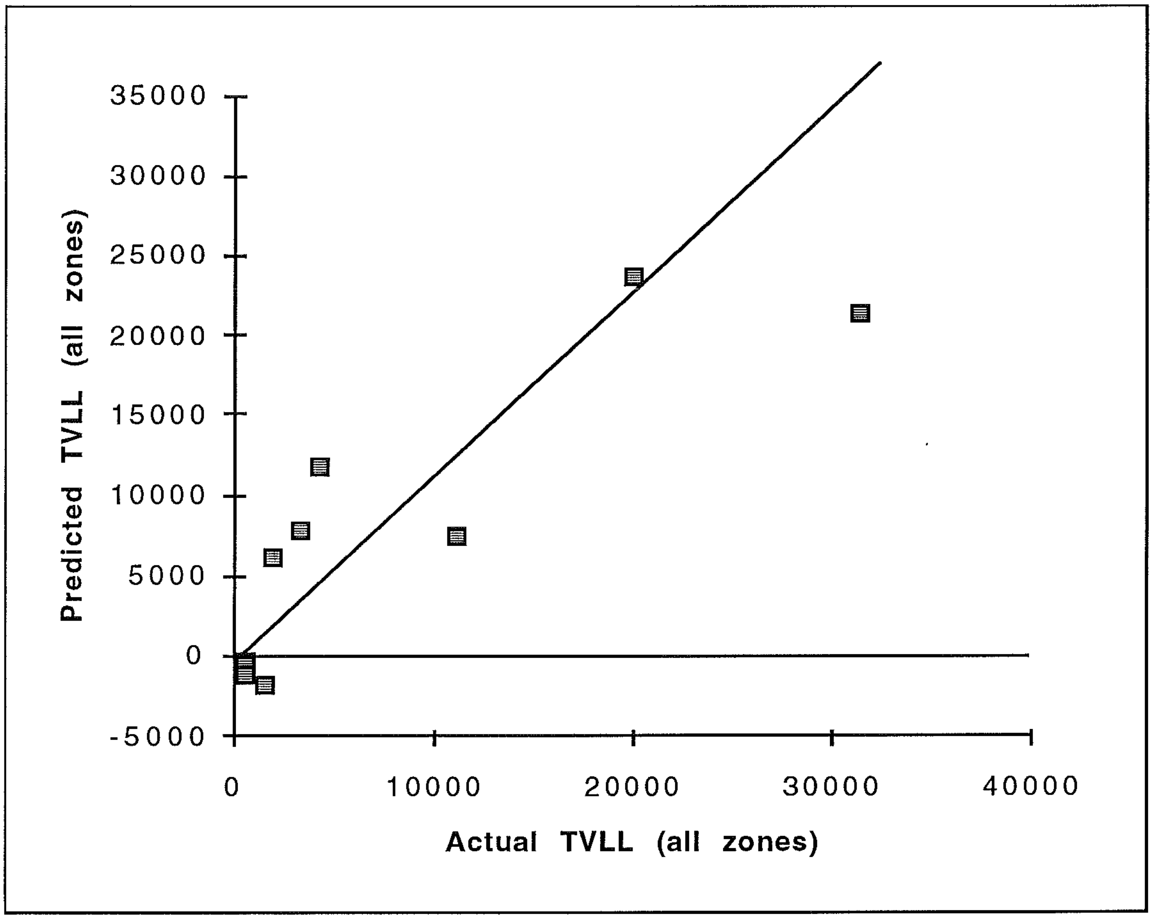


Figure 25 Predicted versus observed Total Volumetric Land Loss (TVLL) at Tuktoyaktuk.

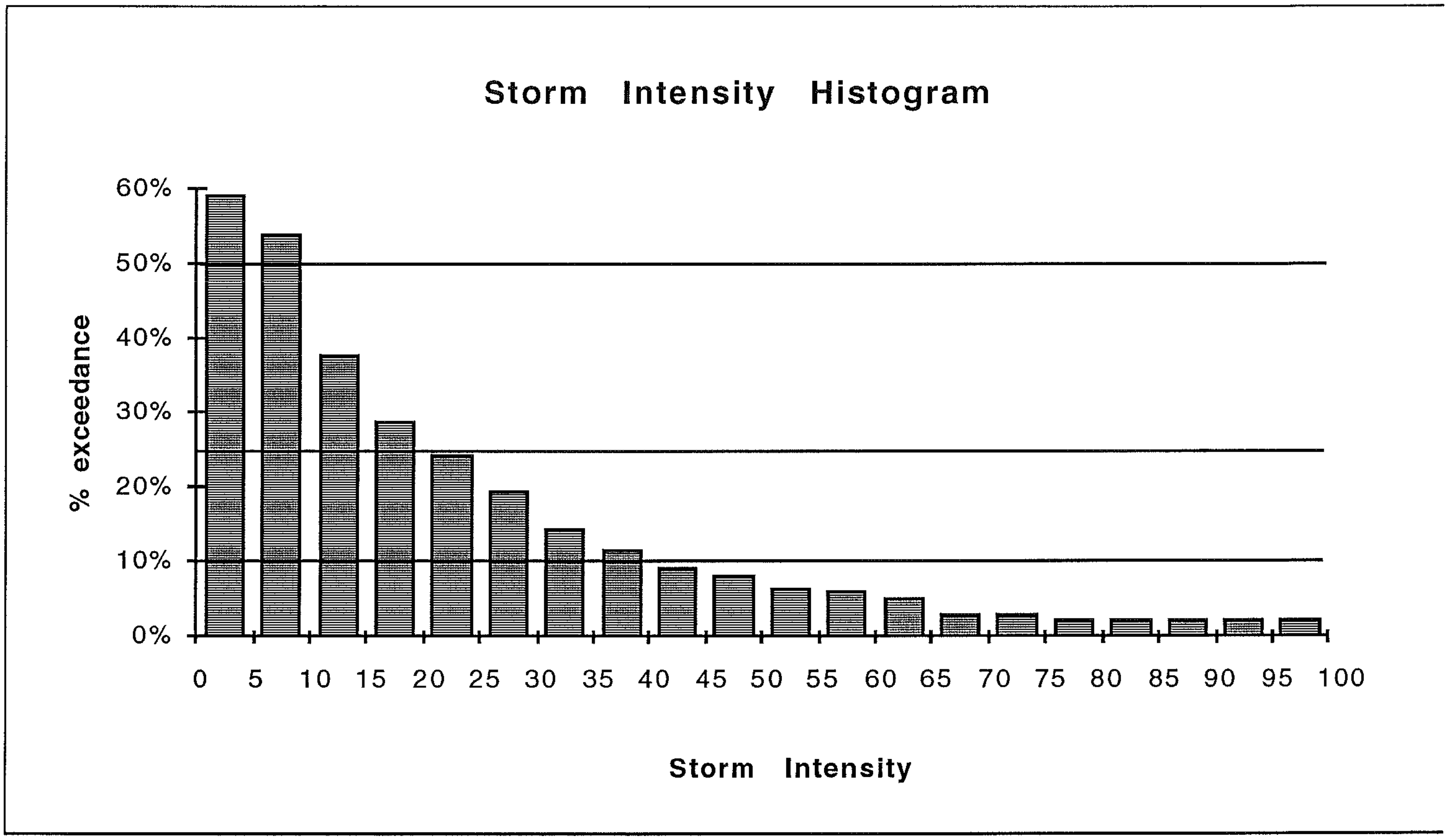


Figure 26 Histogram of storm intensity at Tuktoyaktuk for all events in the database.

Figure 27 Receding shoreline at North Head.

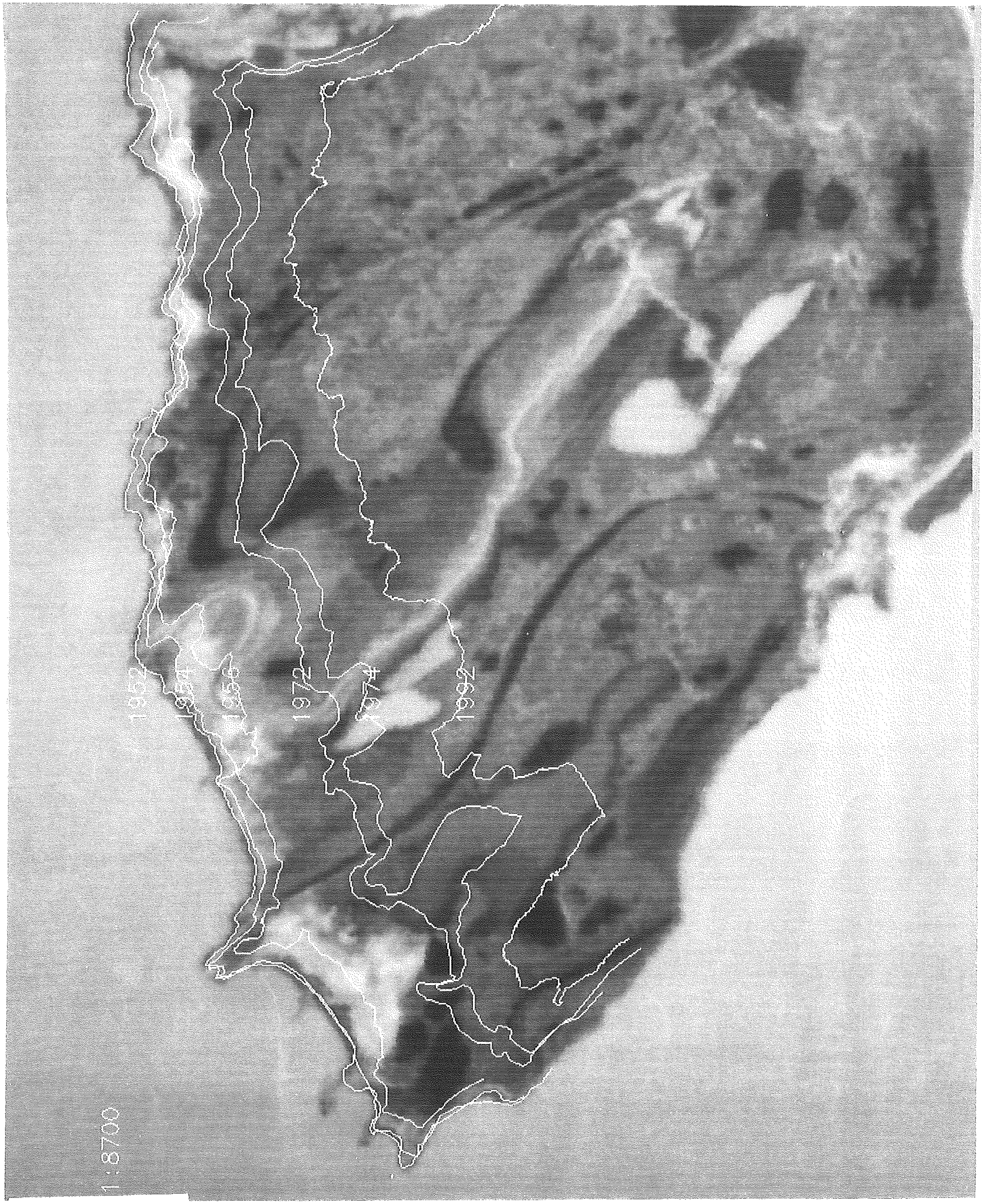


Figure 28 Receding shoreline at Tent Island overlain on the 1952 air photograph

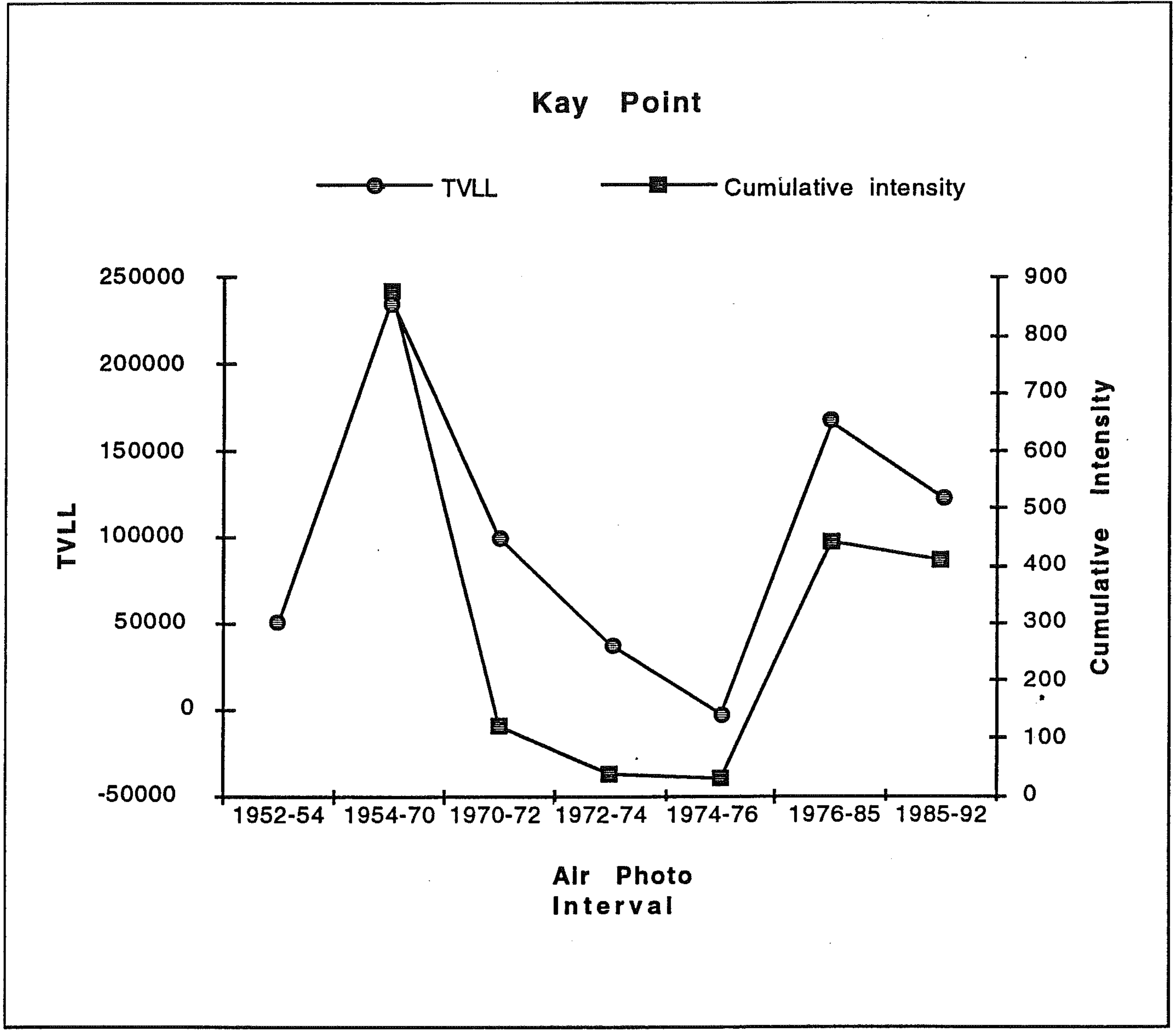


Figure 29 Time series of adjusted cumulative storm intensity (1954-1992) and total volumetric land loss (TVLL) (1952-1992) at Kay Point, Yukon Territories.

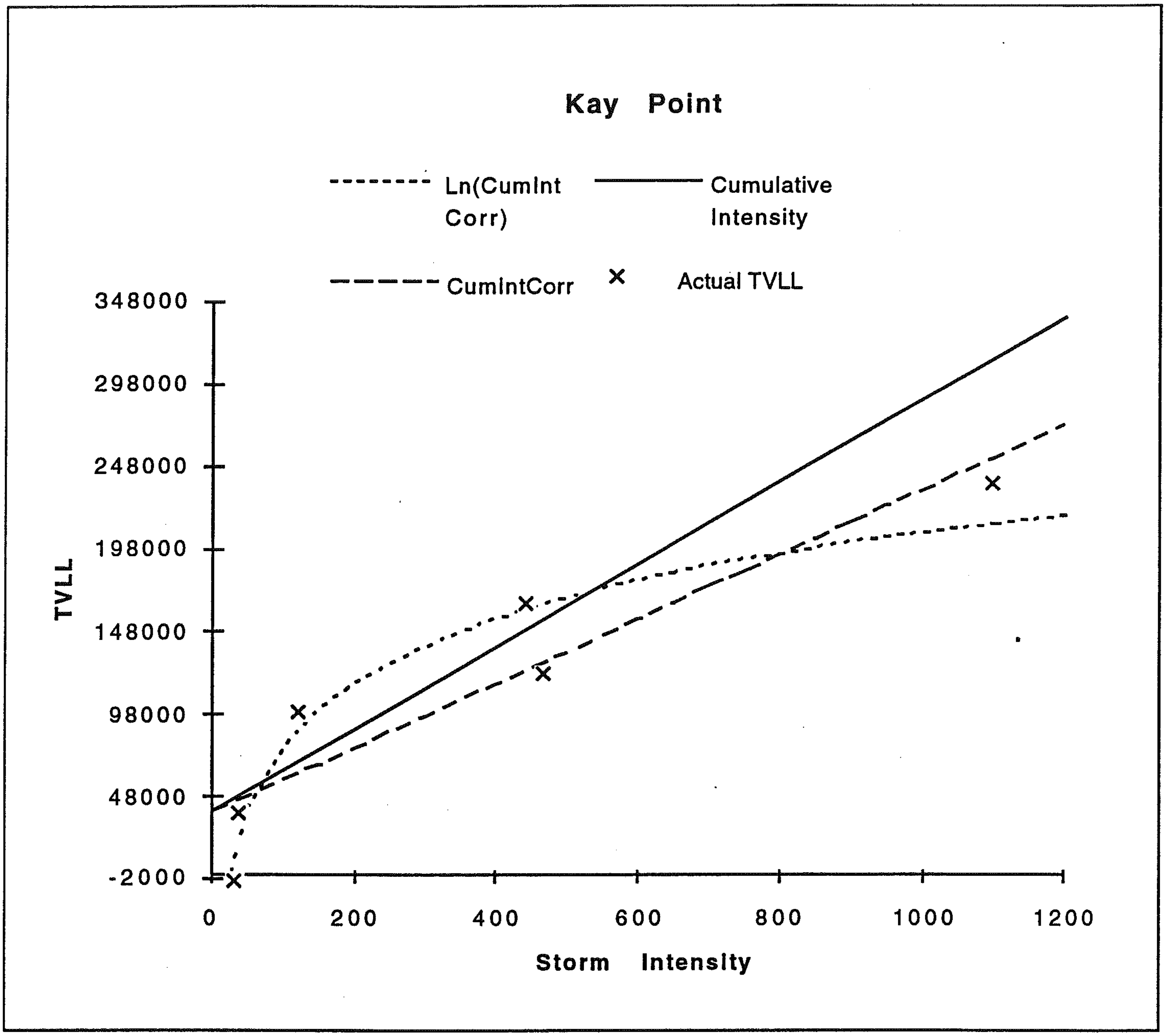


Figure 30 Regression of TVLL on storm intensity at Kay Point. CumIntcorr is the cumulative storm intensity for each air photo interval corrected for missing climate data (see text for further explanation). Ln(CumIntCorr) is the natural logarithm of the CumIntcorr.

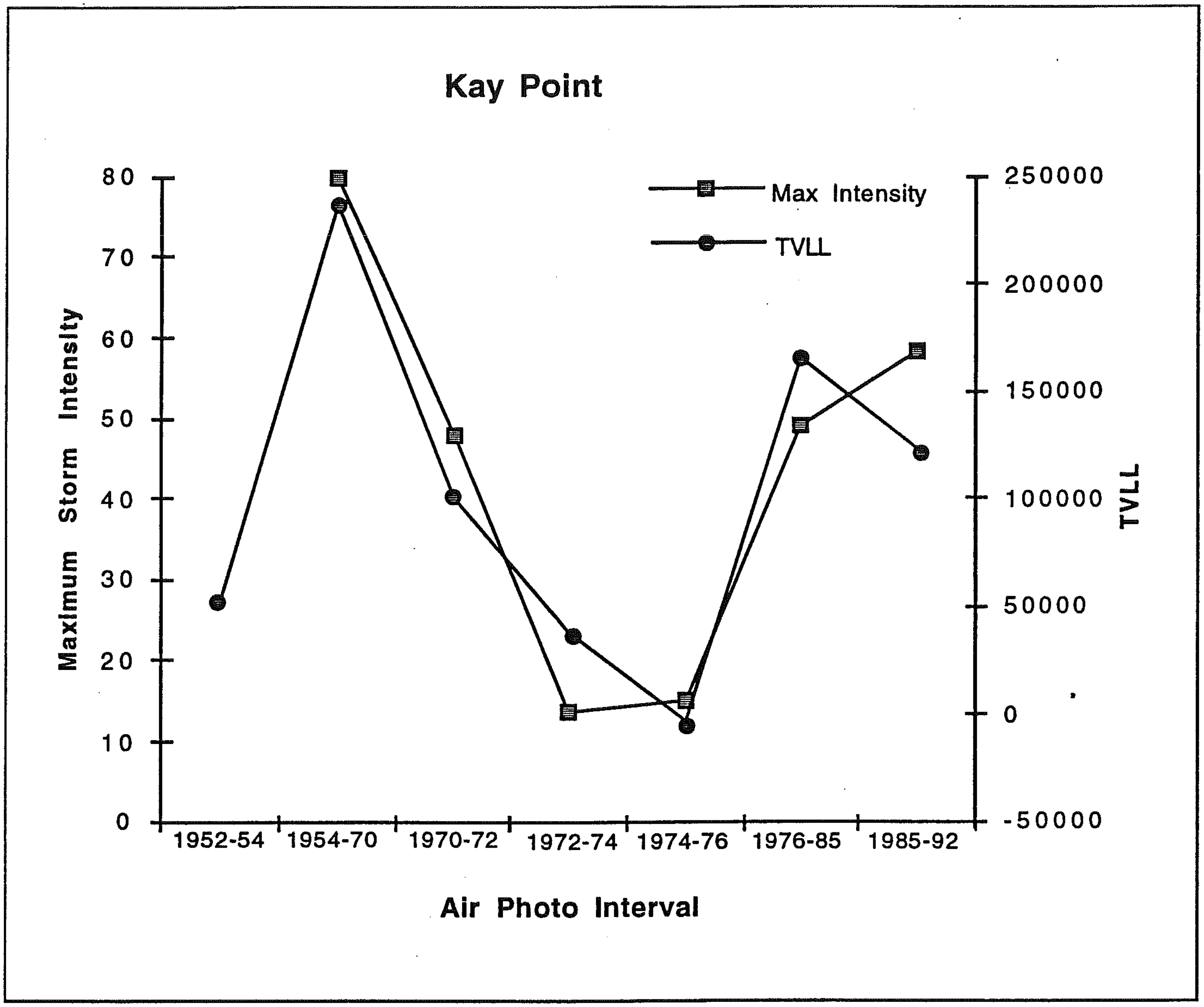


Figure 31 Time series of maximum storm intensity and TVLL at Kay Point, Yukon Territories.

Appendix A

Comparison between digital and analog methods for measurement of coastal erosion.

Analysis of Coastal Erosion:
A Comparison between digital and traditional analog methods

In order to ascertain the ability of new digital techniques to approximate the level of accuracy attainable via traditional methods a comparison was made using the database from the Flagpole zone (see Figure 3) at Tuktoyaktuk.The traditional method (TM) employed a stereoplotter to recreate the optical geometry of the air photography missions. The TM makes use of stereo pairs to eliminate the problem of parallax; the spatial translation of elevated points when projected onto a two dimensional plane. Geographical referencing was performed using existing aerial triangulation supplied by the Department of Energy, Mines, and Resources. Since detailed features were well-defined on the photographs, the positional accuracy of ground positions using this method was within plus or minus 0.3 to 0.6 m for low level photos and plus or minus 3 to 4 m for the high level photography taken in 1947.

The digital image analysis approach used a public domain Geographical Information System (GIS) called GRASS (Geographical Resources Analysis Support System). Air photos are first digitized via a scanner, then converted to GRASS's matrix representation. The images are then geo-referenced by rectification, a process in which common, control points are chosen on each image then used to generate a transformation equation which is applied to each cell (entry in the matrix) of the rasters. The new, rectified rasters are now all at the same, properly referenced scale and orientation. We assume that the rectification also eliminates problems caused by photographic distortions so no extra steps, called ortho-rectification, are needed to eliminate them.

The final results of the studies were incongruent (see table A1). Differences between the two methods varied from 8% to 264% of the area measured by the TM, the largest errors being associated with the smallest measured values. To understand the sources of these differences, the TM coastline vectors (digitized outline of the coast), were imported into GRASS so direct comparisons could be made. To make this possible, several changes were necessary, first, the GRASS analysis used a digitized 1991 map of Tuktoyaktuk based on the NAD27 datum to geo-reference the air photographs whereas the TM contractor used the NAD83 ellipsoid. After correcting this problem by shifting the TM vectors to the NAD27 model, it was found a small datum shift was still needed to bring both sets to a common reference. It should be noted that this manipulation resulted in a three percent decrease in the area of the buildings as mapped by the TM.

At this point it was found that the two sets of vectors for each year interweaved along the coast rather than overlying exactly. The net area differences between the two methods for the low level photography averaged about 200 m^2, a difference of about 0.67 m over the 300 m length of coast represented by the Flagpole zone. This is equivalent to a positional accuracy of plus or minus 0.67 m for each vector - **identical to the positional accuracy of the TM.** Since we are measuring the difference between two vectors, the positional accuracy must be doubled so that the uncertainty is plus or minus 1.4 m of linear measurement or plus or minus 420 m^2 for the Flagpole zone segment. All of the differences between the TM and GRASS areas fall within or close to the value.

Table A1:
Differences between TM and GRASS measured areas (m^2) at Flagpole Zone

Year	**TM**	**GRASS**	**Difference**	**Equivalent Average Linear retreat (m)**
68-74	3230	2994.73	235.27	11
74-78	720	1218.07	-498.07	2.4
78-79	200	444.17	-244.17	0.7
79-80	20	-32.81	52.81	0.1
80-82	1930	1430.47	499.53	6.4
82-83	100	155.93	-55.93	0.3
83-84	260	371.33	-111.33	0.9
84-85	440	168.03	271.97	1.5
85-86	960	1201.12	-241.12	3.2

In conclusion, the digital method is indeed a viable means of coastal analysis within certain limitations. Erosion rates,of less than about 3 m of linear retreat between photos, will be inaccurate and are just as likely to show advance as retreat, but as erosion increases, results become more dependable.

Appendix B

Storm statistics and fetch distances

Storm statistics are based on a search of the Atmospheric Environment Services LAST database from the Tuktoyaktuk DEW line site. Search criteria were winds which exceeded 37 km/hr for a minimum of 6 hours. Easterly and southerly storms may be underrepresented since these directions are over land rather than ocean. The fetch data were measured from ice charts compiled by the Ice Climatology Centre of the Atmospheric Environment Services. The three tenths ice edge was used as point at which wave generation commenced. Effective fetch was calculated according to the technique provided by the U.S. Army Corps of Engineers Shore Protection Manuals (please refer to the text for additional details.

NH - North Head
Tent - Tent Island
Tuk - Tuktoyaktuk
Kay - Kay Point
Eff fetch - effective fetch
Hs - significant wave height
Intensity - storm intensity index (product of Hs and duration)
Mean direction - vector average of storm wind direction throughout the storm duration
Duration - storm duration
Max wind - maximum observed wind speed in kilometres per hour
Min wind - minimum observed wind speed in kilometres per hour

Date	Eff Fetch (NH) kilometres	Hs (NH) metres	Intensity (NH) metre-hours	Eff Fetch (Tent) kilometres	Hs(Tent) metres	Intensity (Tent) metre-hours
1959-07-09	98.2	2.4	17.0	11.1	1.0	7.1
1959-07-27	84.3	1.7	11.6	64.0	1.5	10.5
1959-08-01	50.3	1.5	19.3	71.0	1.7	21.9
1959-10-03	0.0	0.0	0.0	0.0	0.0	0.0
1959-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1959-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1960-07-24	122.5	2.0	38.3	45.6	1.4	26.7
1960-08-15	182.6	1.9	25.1	27.4	1.0	12.9
1960-08-20	267.0	2.6	80.0	153.9	2.2	67.5
1960-09-12	59.4	1.7	11.9	12.0	0.9	6.3
1960-09-14	277.1	2.8	36.2	130.9	2.2	28.5
1960-09-17	288.5	2.2	15.3	186.9	1.9	13.6
1960-09-19	288.5	2.6	66.0	186.9	2.3	58.0
1960-09-22	158.1	2.0	25.4	19.4	0.9	11.8
1960-09-29	254.4	2.2	29.2	151.7	1.9	25.1
1961-07-21	88.2	1.6	11.3	3.5	0.4	3.1
1961-08-01	155.6	1.8	23.9	55.1	1.3	16.8
1961-08-12	132.7	2.4	16.6	88.2	2.0	14.3
1961-08-24	201.2	2.3	16.1	62.8	1.5	10.8
1961-09-13	158.6	2.0	26.3	19.4	0.9	12.1
1961-09-29	158.1	2.0	37.1	19.4	0.9	17.2
1962-07-04	79.3	1.5	10.3	59.8	1.3	9.3
1962-07-25	131.9	2.2	41.8	95.4	2.0	37.3
1962-07-28	131.9	2.9	37.7	95.4	2.6	33.5
1962-08-26	182.8	2.0	14.3	98.8	1.7	11.7
1962-09-03	238.4	3.4	63.7	128.9	2.7	51.5
1962-09-21	194.8	2.7	19.2	33.3	1.4	10.0
1962-10-11	382.9	3.2	60.9	84.7	2.0	37.3
1962-10-29	92.0	1.7	21.9	0.0	0.0	0.0
1963-07-05	111.2	2.2	28.6	63.1	1.8	23.2
1963-07-27	253.3	2.8	36.4	108.8	2.1	27.5
1963-07-29	290.2	3.5	88.1	193.8	3.1	77.2
1963-08-04	321.7	2.8	19.4	240.0	2.5	17.8
1963-08-10	258.2	2.1	14.9	177.3	1.9	13.4
1963-08-23	5.6	0.6	4.4	0.0	0.0	0.0
1963-08-26	178.2	2.3	16.3	122.4	2.0	14.3
1963-08-31	158.1	1.8	12.9	19.4	0.9	6.0
1963-10-02	282.3	3.2	22.5	507.6	3.8	26.5
1963-10-03	584.6	4.2	79.2	342.2	3.6	68.5
1963-10-07	158.1	2.0	48.8	19.4	0.9	22.6
1963-10-16	0.0	0.0	0.0	0.0	0.0	0.0
1963-10-21	0.0	0.0	0.0	0.0	0.0	0.0
1964-07-10	11.8	0.9	22.0	56.5	1.6	41.0
1964-07-18	0.0	0.0	0.0	31.9	1.2	15.9
1964-08-13	40.5	1.5	10.7	19.4	1.1	7.9
1964-08-19	61.8	1.6	39.5	92.5	1.8	45.8
1964-09-03	21.3	1.2	31.0	134.1	2.5	62.8
1965-07-05	0.0	0.0	0.0	38.0	1.1	7.9
1965-08-06	190.0	3.2	41.9	125.3	2.8	36.2
1965-08-12	155.2	1.9	13.6	77.2	1.5	10.7
1965-09-01	161.2	1.9	13.0	147.6	1.8	12.7
1965-09-04	180.4	1.9	13.5	144.8	1.8	12.6
1965-09-20	179.8	2.7	66.7	116.5	2.3	57.4
1965-09-28	219.5	2.6	33.3	154.5	2.3	29.7
1965-10-12	156.0	1.9	13.6	64.8	1.4	10.1
1966-09-10	161.6	2.1	14.5	76.5	1.6	11.2

Date	Eff Fetch (NH) kilometres	Hs (NH) metres	Intensity (NH) metre-hours	Eff Fetch (Tent) kilometres	Hs(Tent) metres	Intensity (Tent) metre-hours
1966-09-26	23.1	1.0	13.6	6.6	0.6	8.2
1966-10-04	71.2	1.5	10.3	12.0	0.7	5.1
1967-07-24	49.9	1.5	10.3	67.3	1.7	11.6
1967-09-01	26.1	1.0	7.1	27.4	1.0	7.3
1967-09-17	158.1	2.0	13.7	19.4	0.9	6.3
1967-09-18	158.1	2.5	32.3	19.4	1.1	14.6
1967-10-03	109.1	2.2	15.3	100.2	2.1	14.8
1967-10-03	91.0	1.8	12.9	102.6	1.9	13.5
1968-07-09	0.0	0.0	0.0	0.0	0.0	0.0
1968-10-03	726.8	3.5	45.1	369.2	3.0	38.6
1968-10-24	165.9	2.3	29.5	23.6	1.1	14.3
1968-10-25	28.7	1.2	60.9	6.8	0.7	34.0
1969-07-10	0.0	0.0	0.0	30.0	1.1	7.5
1969-08-04	87.9	1.6	20.9	2.7	0.4	5.3
1969-08-05	110.3	2.2	15.5	72.9	1.9	13.4
1969-08-16	23.8	1.3	40.2	48.2	1.7	53.2
1969-08-20	24.4	1.3	16.6	49.7	1.7	22.0
1970-09-05	350.7	2.7	34.9	254.5	2.5	32.0
1970-09-14	319.9	5.0	35.2	190.5	4.2	29.3
1970-09-14	289.8	2.2	15.4	216.3	2.0	14.2
1970-10-01	25.5	1.1	8.0	0.0	0.0	0.0
1970-10-11	144.9	1.8	12.6	0.0	0.0	0.0
1970-10-12	195.6	2.8	36.7	0.0	0.0	0.0
1970-10-21	0.0	0.0	0.0	0.0	0.0	0.0
1971-07-29	51.3	1.6	11.5	0.0	0.0	0.0
1971-08-03	306.2	2.2	28.9	280.3	2.2	28.3
1971-08-22	300.5	2.7	66.7	261.6	2.6	64.2
1971-10-19	0.0	0.0	0.0	0.0	0.0	0.0
1972-09-01	565.6	4.0	52.2	299.8	3.4	43.8
1972-09-11	509.8	2.7	34.5	448.8	2.6	33.6
1972-09-19	388.6	2.4	16.5	18.1	0.8	5.9
1972-09-27	501.2	2.9	20.5	242.7	2.4	17.0
1972-10-16	0.0	0.0	0.0	0.0	0.0	0.0
1972-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1972-10-30	0.0	0.0	0.0	0.0	0.0	0.0
1973-07-13	100.7	1.6	11.2	30.6	1.0	7.2
1974-08-19	53.1	1.7	22.0	83.6	2.0	26.1
1974-09-02	48.6	1.3	8.9	83.6	1.6	10.9
1974-10-25	0.0	0.0	0.0	0.0	0.0	0.0
1975-08-10	204.2	2.7	34.6	67.7	1.8	23.5
1975-08-27	185.7	2.8	19.9	87.8	2.2	15.3
1975-09-25	53.2	1.3	17.4	61.7	1.4	18.4
1975-10-27	0.0	0.0	0.0	0.0	0.0	0.0
1975-10-28	0.0	0.0	0.0	0.0	0.0	0.0
1975-10-30	0.0	0.0	0.0	0.0	0.0	0.0
1976-07-06	0.0	0.0	0.0	10.1	0.7	9.0
1976-08-12	206.8	2.6	48.5	55.8	1.6	30.6
1976-09-30	275.2	2.2	15.2	283.5	2.2	15.3
1976-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1977-08-27	419.9	3.1	58.3	221.7	2.6	48.8
1977-09-24	15.7	0.8	5.9	0.0	0.0	0.0
1977-10-15	0.0	0.0	0.0	85.2	1.7	22.0
1978-07-14	7.0	0.6	7.4	38.0	1.1	14.6
1978-09-20	242.0	2.3	15.8	30.6	1.1	7.7
1978-10-06	0.0	0.0	0.0	0.0	0.0	0.0
1978-10-08	0.0	0.0	0.0	0.0	0.0	0.0

Date	Eff Fetch (NH) kilometres	Hs (NH) metres	Intensity (NH) metre-hours	Eff Fetch (Tent) kilometres	Hs(Tent) metres	Intensity (Tent) metre-hours
1978-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1978-10-23	0.0	0.0	0.0	0.0	0.0	0.0
1979-07-27	165.9	2.1	14.9	23.6	1.0	7.3
1979-08-04	212.2	2.2	15.2	139.6	1.9	13.4
1980-07-26	255.0	2.6	18.1	214.5	2.5	17.2
1980-08-17	254.9	2.5	17.5	68.0	1.6	11.3
1980-08-30	250.2	2.4	16.8	106.9	1.8	12.9
1980-09-16	155.2	2.2	28.9	41.0	1.4	17.8
1980-09-27	0.0	0.0	0.0	0.0	0.0	0.0
1980-09-27	0.0	0.0	0.0	0.0	0.0	0.0
1981-07-29	136.1	1.8	12.3	66.6	1.4	9.7
1981-08-02	201.4	2.4	74.8	150.1	2.2	68.1
1981-08-16	140.6	2.1	53.7	28.8	1.2	29.9
1981-08-21	165.9	1.9	13.1	23.6	0.9	6.5
1981-08-30	44.4	1.4	69.3	31.0	1.2	60.3
1981-09-16	502.2	2.9	54.5	367.9	2.7	50.7
1981-09-28	279.7	2.2	28.3	81.0	1.5	19.3
1981-10-04	193.0	2.5	93.8	18.1	1.0	38.8
1981-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1981-10-31	0.0	0.0	0.0	0.0	0.0	0.0
1982-07-27	252.2	2.4	16.9	164.5	2.1	14.8
1982-08-21	158.1	2.2	29.0	79.9	1.8	22.9
1982-09-17	696.2	4.1	29.0	411.6	3.6	25.5
1982-09-20	163.5	2.3	29.4	18.3	1.0	13.0
1982-10-02	660.3	2.6	18.3	241.9	2.1	14.6
1982-10-20	0.0	0.0	0.0	0.0	0.0	0.0
1982-10-19	0.0	0.0	0.0	0.0	0.0	0.0
1982-10-23	0.0	0.0	0.0	0.0	0.0	0.0
1983-07-02	17.2	0.8	5.8	18.3	0.8	5.9
1983-08-03	177.2	2.2	15.7	92.9	1.8	12.6
1983-09-02	227.6	2.1	14.4	154.8	1.8	12.9
1983-09-15	19.3	1.0	6.9	34.6	1.2	8.7
1983-09-22	21.7	1.0	24.8	52.0	1.4	34.8
1983-09-25	33.0	1.1	20.2	52.9	1.3	24.1
1983-10-04	0.0	0.0	0.0	0.0	0.0	0.0
1983-10-07	0.0	0.0	0.0	0.0	0.0	0.0
1984-07-13	101.8	1.6	11.2	60.8	1.3	9.4
1984-07-18	106.1	2.0	37.1	45.3	1.4	27.1
1984-08-08	12.5	0.9	6.0	0.0	0.0	0.0
1984-08-10	154.4	2.4	115.5	116.0	2.1	104.7
1984-08-15	162.0	2.5	17.3	59.6	1.7	12.0
1984-08-25	61.8	2.1	76.1	117.9	2.6	97.1
1984-10-24	0.0	0.0	0.0	0.0	0.0	0.0
1985-07-05	0.0	0.0	0.0	28.8	1.2	22.7
1985-07-19	0.0	0.0	0.0	57.5	1.7	11.6
1985-09-15	310.6	2.6	17.9	165.3	2.1	14.9
1985-09-16	310.6	3.1	152.8	165.3	2.6	125.3
1985-09-29	126.5	1.8	12.5	13.8	0.8	5.4
1985-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1986-07-19	0.0	0.0	0.0	162.6	2.0	14.0
1986-08-21	443.9	3.0	21.0	327.9	2.8	19.5
1986-08-23	363.2	3.8	72.6	679.3	4.5	85.9
1986-09-21	55.4	1.4	10.1	0.0	0.0	0.0
1986-10-01	141.0	2.0	14.1	21.5	1.0	7.0
1986-10-04	27.3	1.0	6.9	4.8	0.5	3.4
1986-10-05	158.8	2.8	71.2	23.1	1.4	34.0

Date	Eff Fetch (NH) kilometres	Hs (NH) metres	Intensity (NH) metre-hours	Eff Fetch (Tent) kilometres	Hs(Tent) metres	Intensity (Tent) metre-hours
1986-10-10	15.0	0.9	11.6	0.0	0.0	0.0
1986-10-25	0.0	0.0	0.0	0.0	0.0	0.0
1987-08-09	363.2	2.8	52.4	679.3	3.2	60.3
1987-08-23	314.3	3.0	20.9	533.4	3.4	24.0
1987-08-28	806.3	3.9	51.2	324.0	3.2	41.0
1987-08-30	716.1	3.5	44.9	340.8	2.9	37.8
1987-08-31	612.6	3.7	70.6	17.4	1.1	20.6
1987-09-05	323.4	3.2	41.0	240.7	2.9	37.5
1987-09-08	266.3	2.6	34.1	103.4	1.9	25.1
1987-10-26	0.0	0.0	0.0	0.0	0.0	0.0
1988-07-02	0.0	0.0	0.0	23.6	1.0	7.0
1988-07-22	253.5	2.1	14.8	130.0	1.7	12.2
1988-08-01	12.8	0.8	10.6	0.0	0.0	0.0
1988-08-03	144.6	2.4	46.4	99.2	2.1	40.6
1988-08-13	86.0	1.6	20.4	34.1	1.1	14.5
1988-09-06	118.0	1.8	12.6	71.4	1.5	10.6
1988-09-16	161.6	1.9	13.0	68.9	1.4	9.8
1988-10-08	138.4	1.8	12.4	32.1	1.1	7.4
1988-10-14	0.0	0.0	0.0	0.0	0.0	0.0
1988-10-16	0.0	0.0	0.0	0.0	0.0	0.0
1989-07-19	59.9	1.4	10.0	2.7	0.4	2.9
1989-08-15	122.2	1.7	11.9	62.4	1.4	9.5
1989-08-21	140.4	1.9	13.4	101.5	1.7	12.0
1989-09-16	265.3	2.8	36.4	176.7	2.5	32.0
1989-09-18	305.8	3.1	59.0	232.9	2.9	54.3
1989-09-24	28.7	1.0	7.1	6.8	0.6	4.0
1989-09-26	459.7	2.7	34.5	0.0	0.0	0.0
1989-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1989-10-20	0.0	0.0	0.0	0.0	0.0	0.0
1990-08-27	452.7	3.1	21.9	243.3	2.6	18.5
1990-09-01	452.0	3.6	46.4	419.3	3.5	45.4
1990-09-03	499.6	3.0	56.6	377.4	2.8	52.9
1990-09-07	126.4	2.2	28.6	123.6	2.2	28.4
1990-09-09	137.6	2.2	15.4	151.6	2.3	15.9
1990-10-24	176.5	2.1	39.1	30.6	1.1	20.9
1991-08-04	51.1	1.6	20.5	93.6	2.0	25.7
1991-08-24	71.4	1.7	11.8	57.6	1.6	10.9
1991-10-08	97.3	1.9	25.3	3.6	0.5	6.8
1991-10-13	28.7	1.2	37.0	6.8	0.7	20.7
1991-10-20	0.0	0.0	0.0	0.0	0.0	0.0
1991-10-23	0.0	0.0	0.0	0.0	0.0	0.0
1992-09-09	215.5	2.0	14.2	184.1	1.9	13.6
1992-09-16	169.1	2.4	30.6	103.6	2.0	25.9
1992-09-22	115.9	1.9	48.7	33.0	1.2	30.6

Date	Eff fetch (Tuk) kilometres	Hs (Tuk) metres	Intensity (Tuk) metre-hours	Eff Fetch (Kay) kilometres	Hs (Kay) metres	Intensity (Kay) metre-hours
1959-07-09	18.0	1.2	8.7	0.0	0.0	0.0
1959-07-27	28.6	1.1	7.7	2.3	0.4	2.8
1959-08-01	36.5	1.3	17.0	4.8	0.6	7.5
1959-10-03	0.0	0.0	0.0	0.0	0.0	0.0
1959-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1959-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1960-07-24	71.4	1.7	31.7	3.7	0.5	9.6
1960-08-15	0.0	0.0	0.0	249.2	2.1	27.4
1960-08-20	140.5	2.1	65.5	3.7	0.5	15.7
1960-09-12	0.0	0.0	0.0	140.8	2.3	16.2
1960-09-14	71.4	1.8	23.0	3.7	0.5	7.0
1960-09-17	168.2	1.9	13.2	32.0	1.1	7.4
1960-09-19	131.4	2.1	51.7	32.0	1.2	30.7
1960-09-22	0.0	0.0	0.0	229.2	2.2	28.4
1960-09-29	204.0	2.1	27.4	4.8	0.5	6.7
1961-07-21	81.8	1.6	11.0	0.0	0.0	0.0
1961-08-01	139.9	1.8	23.1	0.0	0.0	0.0
1961-08-12	108.7	2.2	15.5	4.8	0.6	4.5
1961-08-24	114.7	1.9	13.4	214.1	2.3	16.4
1961-09-13	0.0	0.0	0.0	250.1	2.3	30.2
1961-09-29	0.0	0.0	0.0	268.6	2.3	43.3
1962-07-04	84.1	1.5	10.5	0.0	0.0	0.0
1962-07-25	0.0	0.0	0.0	9.1	0.8	14.8
1962-07-28	95.8	2.6	33.5	9.1	1.0	13.1
1962-08-26	114.7	1.8	12.3	3.7	0.5	3.2
1962-09-03	102.9	2.5	47.4	3.7	0.7	12.4
1962-09-21	198.6	2.8	19.3	0.0	0.0	0.0
1962-10-11	0.0	0.0	0.0	472.0	3.4	64.2
1962-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1963-07-05	45.0	1.6	20.4	3.7	0.6	7.3
1963-07-27	130.3	2.5	32.8	0.0	0.0	0.0
1963-07-29	196.1	3.1	77.5	4.8	0.7	18.0
1963-08-04	263.7	2.6	18.3	50.9	1.5	10.4
1963-08-10	236.3	2.1	14.6	47.6	1.2	8.6
1963-08-23	0.0	0.0	0.0	0.0	0.0	0.0
1963-08-26	130.5	2.1	14.7	11.7	0.8	5.8
1963-08-31	0.0	0.0	0.0	269.7	2.2	15.1
1963-10-02	291.9	3.2	22.7	251.4	3.1	21.7
1963-10-03	0.0	0.0	0.0	0.0	0.0	0.0
1963-10-07	0.0	0.0	0.0	269.7	2.3	57.1
1963-10-16	0.0	0.0	0.0	0.0	0.0	0.0
1963-10-21	0.0	0.0	0.0	0.0	0.0	0.0
1964-07-10	0.0	0.0	0.0	0.0	0.0	0.0
1964-07-18	0.0	0.0	0.0	0.0	0.0	0.0
1964-08-13	0.0	0.0	0.0	113.4	2.2	15.7
1964-08-19	31.8	1.2	30.6	17.0	1.0	23.9
1964-09-03	38.4	1.6	39.2	18.2	1.2	29.1
1965-07-05	0.0	0.0	0.0	0.0	0.0	0.0
1965-08-06	128.1	2.8	36.5	10.1	1.0	13.3
1965-08-12	128.1	1.8	12.8	4.8	0.5	3.6
1965-09-01	195.6	2.0	13.8	22.1	0.9	6.4
1965-09-04	185.1	1.9	13.6	0.0	0.0	0.0
1965-09-20	130.9	2.4	59.8	41.3	1.6	38.9
1965-09-28	216.5	2.5	33.1	4.8	0.6	7.7
1965-10-12	76.6	1.5	10.7	0.0	0.0	0.0
1966-09-10	0.0	0.0	0.0	152.7	2.0	14.2

Date	Eff fetch (Tuk) kilometres	Hs (Tuk) metres	Intensity (Tuk) metre-hours	Eff Fetch (Kay) kilometres	Hs (Kay) metres	Intensity (Kay) metre-hours
1966-09-26	0.0	0.0	0.0	57.6	1.5	19.4
1966-10-04	0.0	0.0	0.0	140.8	1.8	12.9
1967-07-24	52.0	1.5	10.5	0.0	0.0	0.0
1967-09-01	0.0	0.0	0.0	178.3	2.0	14.2
1967-09-17	0.0	0.0	0.0	199.4	2.1	14.7
1967-09-18	0.0	0.0	0.0	199.4	2.7	34.8
1967-10-03	0.0	0.0	0.0	0.0	0.0	0.0
1967-10-03	0.0	0.0	0.0	0.0	0.0	0.0
1968-07-09	0.0	0.0	0.0	0.0	0.0	0.0
1968-10-03	0.0	0.0	0.0	3.9	0.5	7.0
1968-10-24	0.0	0.0	0.0	201.8	2.4	31.4
1968-10-25	0.0	0.0	0.0	59.0	1.6	80.6
1969-07-10	0.0	0.0	0.0	0.0	0.0	0.0
1969-08-04	0.0	0.0	0.0	0.0	0.0	0.0
1969-08-05	97.1	2.1	14.8	5.1	0.7	4.6
1969-08-16	94.7	2.2	68.7	0.0	0.0	0.0
1969-08-20	82.0	2.0	26.6	0.0	0.0	0.0
1970-09-05	306.1	2.6	33.7	56.7	1.5	19.3
1970-09-14	183.9	4.1	29.0	3.9	0.9	6.1
1970-09-14	198.6	2.0	13.9	5.1	0.5	3.5
1970-10-01	42.0	1.4	9.7	0.0	0.0	0.0
1970-10-11	120.7	1.7	11.9	0.0	0.0	0.0
1970-10-12	120.7	2.4	31.1	44.0	1.6	21.2
1970-10-21	0.0	0.0	0.0	0.0	0.0	0.0
1971-07-29	109.6	2.2	15.3	0.0	0.0	0.0
1971-08-03	275.0	2.2	28.1	120.7	1.7	22.1
1971-08-22	242.3	2.5	62.8	112.0	2.0	48.9
1971-10-19	0.0	0.0	0.0	0.0	0.0	0.0
1972-09-01	321.7	3.4	44.7	67.8	2.0	26.1
1972-09-11	239.1	2.2	28.7	5.1	0.5	6.8
1972-09-19	35.8	1.1	7.7	0.0	0.0	0.0
1972-09-27	278.3	2.5	17.7	5.1	0.6	3.9
1972-10-16	0.0	0.0	0.0	0.0	0.0	0.0
1972-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1972-10-30	0.0	0.0	0.0	0.0	0.0	0.0
1973-07-13	0.0	0.0	0.0	0.0	0.0	0.0
1974-08-19	77.4	2.0	25.4	16.3	1.1	13.8
1974-09-02	75.0	1.5	10.4	10.2	0.7	4.8
1974-10-25	0.0	0.0	0.0	0.0	0.0	0.0
1975-08-10	136.7	2.3	30.3	3.9	0.6	7.4
1975-08-27	123.4	2.5	17.3	3.9	0.6	4.4
1975-09-25	62.5	1.4	18.5	0.0	0.0	0.0
1975-10-27	0.0	0.0	0.0	0.0	0.0	0.0
1975-10-28	0.0	0.0	0.0	0.0	0.0	0.0
1975-10-30	0.0	0.0	0.0	0.0	0.0	0.0
1976-07-06	32.6	1.1	14.4	0.0	0.0	0.0
1976-08-12	0.0	0.0	0.0	188.5	2.5	47.1
1976-09-30	367.8	2.3	16.3	158.3	1.8	12.9
1976-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1977-08-27	276.9	2.7	52.1	3.9	0.5	10.3
1977-09-24	0.0	0.0	0.0	28.4	1.1	7.5
1977-10-15	0.0	0.0	0.0	314.2	2.6	33.3
1978-07-14	0.0	0.0	0.0	0.0	0.0	0.0
1978-09-20	0.0	0.0	0.0	331.3	2.5	17.2
1978-10-06	0.0	0.0	0.0	0.0	0.0	0.0
1978-10-08	0.0	0.0	0.0	0.0	0.0	0.0

Date	Eff fetch (Tuk) kilometres	Hs (Tuk) metres	Intensity (Tuk) metre-hours	Eff Fetch (Kay) kilometres	Hs (Kay) metres	Intensity (Kay) metre-hours
1978-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1978-10-23	0.0	0.0	0.0	0.0	0.0	0.0
1979-07-27	0.0	0.0	0.0	210.7	2.3	16.0
1979-08-04	171.0	2.0	14.3	5.1	0.5	3.7
1980-07-26	152.3	2.2	15.4	32.1	1.2	8.7
1980-08-17	0.0	0.0	0.0	287.6	2.6	18.1
1980-08-30	35.8	1.2	8.6	0.0	0.0	0.0
1980-09-16	146.8	2.2	28.3	0.0	0.0	0.0
1980-09-27	0.0	0.0	0.0	0.0	0.0	0.0
1980-09-27	0.0	0.0	0.0	0.0	0.0	0.0
1981-07-29	77.7	1.5	10.2	0.0	0.0	0.0
1981-08-02	144.7	2.2	67.2	26.0	1.1	35.5
1981-08-16	123.6	2.1	51.4	0.0	0.0	0.0
1981-08-21	0.0	0.0	0.0	8.5	0.6	4.3
1981-08-30	176.6	2.3	113.4	0.0	0.0	0.0
1981-09-16	178.2	2.2	41.3	3.9	0.5	9.5
1981-09-28	0.0	0.0	0.0	546.6	2.5	32.9
1981-10-04	268.5	2.8	103.9	0.0	0.0	0.0
1981-10-29	0.0	0.0	0.0	0.0	0.0	0.0
1981-10-31	0.0	0.0	0.0	0.0	0.0	0.0
1982-07-27	191.1	2.2	15.5	4.7	0.5	3.8
1982-08-21	144.4	2.2	28.2	4.7	0.6	7.4
1982-09-17	175.0	2.8	19.6	0.0	0.0	0.0
1982-09-20	0.0	0.0	0.0	557.1	3.2	41.1
1982-10-02	245.4	2.1	14.7	0.0	0.0	0.0
1982-10-20	0.0	0.0	0.0	0.0	0.0	0.0
1982-10-19	0.0	0.0	0.0	0.0	0.0	0.0
1982-10-23	0.0	0.0	0.0	0.0	0.0	0.0
1983-07-02	0.0	0.0	0.0	180.8	1.9	13.5
1983-08-03	103.6	1.9	13.1	3.6	0.5	3.5
1983-09-02	246.8	2.1	14.7	131.7	1.7	12.2
1983-09-15	60.6	1.5	10.8	0.0	0.0	0.0
1983-09-22	53.3	1.4	35.1	8.7	0.7	17.1
1983-09-25	53.0	1.3	24.2	7.5	0.6	11.2
1983-10-04	0.0	0.0	0.0	0.0	0.0	0.0
1983-10-07	0.0	0.0	0.0	0.0	0.0	0.0
1984-07-13	71.7	1.4	9.9	0.0	0.0	0.0
1984-07-18	185.5	2.4	44.7	0.0	0.0	0.0
1984-08-08	0.0	0.0	0.0	0.0	0.0	0.0
1984-08-10	153.5	2.4	115.2	4.7	0.6	29.5
1984-08-15	80.2	1.9	13.5	0.0	0.0	0.0
1984-08-25	128.8	2.7	100.3	16.1	1.2	44.5
1984-10-24	0.0	0.0	0.0	0.0	0.0	0.0
1985-07-05	31.2	1.2	23.4	0.0	0.0	0.0
1985-07-19	21.2	1.1	7.8	0.0	0.0	0.0
1985-09-15	50.4	1.4	9.8	3.6	0.5	3.4
1985-09-16	31.2	1.4	67.3	3.6	0.6	27.8
1985-09-29	31.2	1.1	7.5	0.0	0.0	0.0
1985-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1986-07-19	52.2	1.4	9.5	4.7	0.5	3.6
1986-08-21	246.3	2.6	18.0	79.5	1.8	12.3
1986-08-23	248.2	3.4	64.5	79.5	2.3	43.1
1986-09-21	224.6	2.3	16.3	0.0	0.0	0.0
1986-10-01	116.6	1.9	13.2	0.0	0.0	0.0
1986-10-04	0.0	0.0	0.0	56.5	1.3	9.1
1986-10-05	190.1	3.0	75.7	4.7	0.7	17.6

Date	Eff fetch (Tuk) kilometres	Hs (Tuk) metres	Intensity (Tuk) metre-hours	Eff Fetch (Kay) kilometres	Hs (Kay) metres	Intensity (Kay) metre-hours
1986-10-10	0.0	0.0	0.0	0.0	0.0	0.0
1986-10-25	0.0	0.0	0.0	0.0	0.0	0.0
1987-08-09	295.7	2.6	49.6	52.1	1.5	27.7
1987-08-23	190.9	2.6	18.0	0.0	0.0	0.0
1987-08-28	264.2	3.0	38.6	66.0	1.8	23.9
1987-08-30	313.6	2.8	36.9	133.0	2.2	28.3
1987-08-31	31.2	1.4	26.1	0.0	0.0	0.0
1987-09-05	200.9	2.7	35.4	4.7	0.6	8.2
1987-09-08	167.9	2.3	29.6	0.0	0.0	0.0
1987-10-26	0.0	0.0	0.0	0.0	0.0	0.0
1988-07-02	0.0	0.0	0.0	0.0	0.0	0.0
1988-07-22	182.1	1.9	13.5	3.9	0.4	3.1
1988-08-01	32.1	1.2	15.3	0.0	0.0	0.0
1988-08-03	105.9	2.2	41.6	5.1	0.7	12.4
1988-08-13	47.1	1.3	16.4	0.0	0.0	0.0
1988-09-06	169.4	2.0	14.2	11.2	0.7	5.2
1988-09-16	100.0	1.6	11.2	0.0	0.0	0.0
1988-10-08	83.2	1.5	10.5	0.0	0.0	0.0
1988-10-14	32.8	1.2	8.3	0.0	0.0	0.0
1988-10-16	32.0	1.3	32.9	0.0	0.0	0.0
1989-07-19	0.0	0.0	0.0	0.0	0.0	0.0
1989-08-15	125.7	1.7	12.0	5.1	0.5	3.5
1989-08-21	131.0	1.9	13.1	10.3	0.7	5.0
1989-09-16	197.8	2.6	33.2	5.1	0.6	8.1
1989-09-18	233.6	2.9	54.3	54.1	1.7	32.4
1989-09-24	0.0	0.0	0.0	59.0	1.3	9.3
1989-09-26	110.3	1.8	23.0	0.0	0.0	0.0
1989-10-18	0.0	0.0	0.0	0.0	0.0	0.0
1989-10-20	0.0	0.0	0.0	0.0	0.0	0.0
1990-08-27	144.8	2.2	15.7	0.0	0.0	0.0
1990-09-01	142.6	2.5	32.5	5.1	0.7	8.7
1990-09-03	146.0	2.1	40.0	3.9	0.5	9.7
1990-09-07	69.6	1.8	23.1	0.0	0.0	0.0
1990-09-09	76.6	1.8	12.5	3.9	0.5	3.8
1990-10-24	0.0	0.0	0.0	222.2	2.2	41.9
1991-08-04	63.3	1.7	22.3	0.0	0.0	0.0
1991-08-24	51.5	1.5	10.5	0.0	0.0	0.0
1991-10-08	28.4	1.2	15.9	0.0	0.0	0.0
1991-10-13	0.0	0.0	0.0	59.0	1.6	48.8
1991-10-20	0.0	0.0	0.0	0.0	0.0	0.0
1991-10-23	0.0	0.0	0.0	0.0	0.0	0.0
1992-09-09	216.0	2.0	14.2	134.7	1.8	12.3
1992-09-16	91.4	1.9	24.8	0.0	0.0	0.0
1992-09-22	0.0	0.0	0.0	0.0	0.0	0.0

Date	Mean Direction degrees	Duration hours	Max Wind km/hr	Min Wind km/hr
1959-07-09	250	7	58	45
1959-07-27	280	7	40	40
1959-08-01	295	13	48	37
1959-10-03	295	25	56	37
1959-10-18	270	13	40	37
1959-10-29	50	13	48	37
1960-07-24	290	19	47	37
1960-08-15	60	13	37	37
1960-08-20	290	31	47	37
1960-09-12	100	7	48	42
1960-09-14	295	13	48	40
1960-09-17	320	7	37	37
1960-09-19	305	25	45	39
1960-09-22	80	13	40	37
1960-09-29	320	13	40	37
1961-07-21	285	7	40	37
1961-08-01	320	13	37	37
1961-08-12	305	7	56	37
1961-08-24	35	7	45	37
1961-09-13	55	13	42	37
1961-09-29	90	19	40	37
1962-07-04	305	7	37	37
1962-07-25	230	19	51	37
1962-07-28	305	13	72	37
1962-08-26	295	7	40	37
1962-09-03	280	19	64	40
1962-09-21	295	7	47	47
1962-10-11	50	19	51	40
1962-10-29	260	13	42	37
1963-07-05	290	13	47	45
1963-07-27	285	13	53	37
1963-07-29	305	25	58	45
1963-08-04	320	7	48	37
1963-08-10	320	7	37	37
1963-08-23	170	7	50	37
1963-08-26	305	7	45	40
1963-08-31	90	7	37	37
1963-10-02	340	7	50	47
1963-10-03	150	19	64	37
1963-10-07	90	25	40	37
1963-10-16	335	13	45	40
1963-10-21	70	7	42	37
1964-07-10	350	25	50	39
1964-07-18	205	13	47	37
1964-08-13	90	7	48	45
1964-08-19	320	25	47	37
1964-09-03	330	25	60	37
1965-07-05	320	7	37	37
1965-08-06	305	13	60	47
1965-08-12	305	7	40	37
1965-09-01	330	7	37	37
1965-09-04	320	7	37	37
1965-09-20	305	25	55	39
1965-09-28	320	13	47	40
1965-10-12	270	7	40	37
1966-09-10	155	7	40	40

Date	Mean Direction degrees	Duration hours	Max Wind km/hr	Min Wind km/hr
1966-09-26	125	13	43	39
1966-10-04	110	7	39	37
1967-07-24	320	7	45	40
1967-09-01	70	7	40	37
1967-09-17	90	7	40	37
1967-09-18	55	13	55	37
1967-10-03	340	7	55	37
1967-10-03	340	7	48	37
1968-07-09	190	7	40	40
1968-10-03	190	13	50	37
1968-10-24	90	13	48	37
1968-10-25	55	49	51	37
1969-07-10	350	7	40	37
1969-08-04	215	13	40	37
1969-08-05	305	7	56	37
1969-08-16	350	31	60	37
1969-08-20	340	13	50	45
1970-09-05	340	13	45	37
1970-09-14	290	7	71	60
1970-09-14	305	7	37	37
1970-10-01	270	7	45	40
1970-10-11	280	7	37	37
1970-10-12	280	13	56	40
1970-10-21	280	7	47	39
1971-07-29	280	7	47	45
1971-08-03	330	13	37	37
1971-08-22	325	25	47	37
1971-10-19	345	7	37	37
1972-09-01	320	13	51	48
1972-09-11	305	13	40	37
1972-09-19	260	7	37	37
1972-09-27	330	7	45	37
1972-10-16	140	7	40	37
1972-10-29	250	7	37	37
1972-10-30	295	7	45	45
1973-07-13	70	7	37	37
1974-08-19	340	13	51	42
1974-09-02	330	7	39	37
1974-10-25	90	31	42	37
1975-08-10	290	13	51	40
1975-08-27	290	7	56	42
1975-09-25	295	13	40	37
1975-10-27	295	13	40	37
1975-10-28	300	19	45	42
1975-10-30	305	19	40	37
1976-07-06	290	13	40	37
1976-08-12	35	19	51	37
1976-09-30	350	7	37	37
1976-10-18	290	7	40	37
1977-08-27	295	19	50	37
1977-09-24	220	7	41	37
1977-10-15	40	13	44	37
1978-07-14	40	13	37	37
1978-09-20	70	7	41	37
1978-10-06	70	7	37	37
1978-10-08	80	7	37	37

Date	**Mean Direction** degrees	**Duration** hours	**Max Wind** km/hr	**Min Wind** km/hr
1978-10-18	95	7	46	41
1978-10-23	50	7	41	37
1979-07-27	95	7	44	37
1979-08-04	300	7	41	37
1980-07-26	320	7	48	37
1980-08-17	55	7	46	37
1980-08-30	250	7	44	37
1980-09-16	315	13	48	37
1980-09-27	90	7	39	37
1980-09-27	95	7	37	37
1981-07-29	280	7	37	37
1981-08-02	310	31	48	37
1981-08-16	290	25	48	37
1981-08-21	80	7	37	37
1981-08-30	320	49	48	37
1981-09-16	295	19	44	37
1981-09-28	35	13	37	37
1981-10-04	365	37	52	37
1981-10-29	330	7	37	37
1981-10-31	290	6	37	37
1982-07-27	300	7	44	37
1982-08-21	300	13	48	37
1982-09-17	270	7	52	46
1982-09-20	80	13	44	41
1982-10-02	295	7	37	37
1982-10-20	290	31	44	37
1982-10-19	275	7	67	37
1982-10-23	60	7	41	37
1983-07-02	80	7	37	37
1983-08-03	290	7	46	37
1983-09-02	355	7	37	37
1983-09-15	330	7	46	37
1983-09-22	340	25	43	37
1983-09-25	320	19	37	37
1983-10-04	275	7	37	37
1983-10-07	270	7	44	43
1984-07-13	285	7	37	37
1984-07-18	275	19	48	37
1984-08-08	180	7	44	41
1984-08-10	310	49	52	37
1984-08-15	270	7	48	43
1984-08-25	5	37	63	41
1984-10-24	295	31	56	37
1985-07-05	280	19	48	37
1985-07-19	310	7	48	41
1985-09-15	295	7	44	37
1985-09-16	265	49	56	37
1985-09-29	250	7	39	37
1985-10-18	280	31	65	37
1986-07-19	305	7	41	37
1986-08-21	310	7	44	41
1986-08-23	315	19	67	37
1986-09-21	305	7	44	37
1986-10-01	285	7	44	37
1986-10-04	140	7	37	37
1986-10-05	315	25	65	37

Date	Mean Direction degrees	Duration hours	Max Wind km/hr	Min Wind km/hr
1986-10-10	235	13	46	37
1986-10-25	280	7	37	37
1987-08-09	325	19	46	37
1987-08-23	285	7	46	44
1987-08-28	310	13	56	37
1987-08-30	340	13	46	41
1987-08-31	260	19	56	37
1987-09-05	305	13	56	37
1987-09-08	275	13	48	37
1987-10-26	245	7	46	44
1988-07-02	85	7	41	37
1988-07-22	290	7	37	37
1988-08-01	240	13	44	37
1988-08-03	305	19	56	37
1988-08-13	270	13	39	37
1988-09-06	360	7	41	37
1988-09-16	285	7	37	37
1988-10-08	285	7	37	37
1988-10-14	285	7	44	37
1988-10-16	280	25	52	37
1989-07-19	220	7	41	37
1989-08-15	300	7	37	37
1989-08-21	310	7	41	37
1989-09-16	315	13	52	37
1989-09-18	325	19	56	37
1989-09-24	125	7	37	37
1989-09-26	290	13	41	37
1989-10-18	335	7	48	41
1989-10-20	320	7	37	37
1990-08-27	270	7	44	43
1990-09-01	295	13	56	39
1990-09-03	300	19	46	37
1990-09-07	280	13	48	41
1990-09-09	295	7	44	43
1990-10-24	55	19	41	37
1991-08-04	340	13	52	37
1991-08-24	300	7	44	41
1991-10-08	230	13	48	39
1991-10-13	130	31	48	37
1991-10-20	320	13	52	37
1991-10-23	300	7	70	56
1992-09-09	5	7	37	37
1992-09-16	280	13	50	37
1992-09-22	284	25	46	37