PHOTOGRAMMETRIC DATA SET, 1957-2000, AND BATHYMETRIC MEASUREMENTS FOR COLUMBIA GLACIER, ALASKA

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Photogrammetric Data Set, 1957-2000, and Bathymetric Measurements for Columbia Glacier, Alaska

By Robert M. Krimmel

ABSTRACT

Major changes in the length, speed, surface altitude, and calving rate of Columbia Glacier, Alaska have been recorded with stereo vertical photography acquired on 119 dates from 1957 to 2000. Photogrammetric analysis of this photographic record has resulted in precise measurement of these changes. From 1982 to 2000 Columbia Glacier retreated 12 kilometers, reduced its thickness by as much as 400 meters, increased its speed from about 5 to 30 meters per day, and increased its calving rate from 3 to 18 million cubic meters per day. All photogrammetric data for Columbia Glacier from 1957 to 2000 are included in this report, as well as supplemental data of ice-dammed lake surface levels, stagnant ice ablation rate, forebay bathymetry, ground control, and camera calibrations. These data are contained in 481 files, all preserved on a CD-ROM included with this report.

INTRODUCTION

Columbia Glacier enters an inlet in northern Prince William Sound in south central Alaska about 20 kilometers (km) west of Port Valdez, Alaska (fig. 1). This tidewater glacier, about 1,100 square kilometers (km2) in area, has changed very rapidly since 1980, and rapid change contines to the date of this report. Icebergs produced when Columbia Glacier calves sometimes enter shipping lanes, tourism has developed around the glacier, and the rapid changes have generated scientific interest.

An important tool used in the studies of Columbia Glacier is aerial photography and associated photogrammetric measurements. The use of photogrammetry for Columbia Glacier measurements is described in Meier and others (1985). Photogrammetric results for 1957–81 are given by Fountain (1982), and for 1982–92 by Krimmel (1987, 1992). The purpose of this report is to make available the existing photogrammetric data for Columbia Glacier that have not been previously published. In addition, data from the three earlier Columbia Glacier photogrammetric data reports are included in this report so that users of this material will have all data within one report. These previously published data are restricted to the point data only; neither the calculated nor gridded speed data are given. Data in this report require a modest level of programming resource to be fully utilized.

For illustrative purposes some Landsat satellite imagery (figs. 2, 3) is included in this report. Landsat has sufficient resolution to be useful in determining the terminus position, and for some instances can be used for speed measurements, but no attempt has been made to comprehensively include available Landsat or derived terminus positions or speeds in this report.

Ice dynamic modeling efforts, for which the material in this report is targeted, also require ice thickness data. For this reason the available water depth measurements in the forebay (which was ice filled when these data were initiated) are included. The water depth measurements are entirely independent of photogrammetry. These data are contained in 481 files, all preserved on a CD-ROM included with this report. This is the final report for the U.S. Geological Survey (USGS) portion of National Science Foundation grant OPP-9614505 awarded to the USGS and INSTAAR (University of Colorado).

Coordinate System

The North American Datum of 1927 (NAD27), Universal Transverse Mercator (UTM) projection, zone 6 is used as horizontal reference. The National Geodetic Vertical Datum of 1929 is used as vertical reference, and may be referred to simply as “sea level”.

A curvilinear coordinate system along the approximate center of the glacier, with 0 km (zero) at the head of the glacier (fig. 1) is used to describe locations along the center of the glacier. These locations are referred to by an “L” (for Longitudinal), followed by a number that gives the distance from the head of the glacier. For example, “L50” indicates a location near the centerline of the glacier 50 km from the head along the centerline.

The software associated with the analytical stereo plotter used to produce most of the data in this report calculated UTM coordinates to three decimal digits (millimeters). These “over-precise” numbers have been retained. Usually, X, Y, and Z values may be rounded to the nearest meter with no loss to the true precision. The six digit (X) and seven digit (Y) UTM characteristic values have been retained, but constants could be subtracted with no loss to the precision.

Aerial Photography

Photographs used for the photogrammetric measurements given in this report were stereo vertical using 9-inch film in calibrated cameras with a nominal focal length of 6 inches (150 mm). Flight altitude ranged from 2,000 m to 9,000 m, but the most frequent altitude was about 7,000 m. The flight altitude was selected to give the coverage and detail needed. This usually required sufficient height that one photograph would span the width of the glacier and include ground control points on each side of the glacier. For some purposes multiple flight altitudes were used on the same day, which allowed ground control from the smaller scale photography to control more detailed larger scale photography that did not show any permanent control points. Photography prior to October 1991 was black and white, after which color (fig. 4) was sometimes used. Original negatives are in archives of the GeoData Center of the Geophysical Institute of the University of Alaska, Fairbanks, Alaska.

Photogrammetric Analysis of the Photography

Diapositives (first generation positive contact reproductions on transparent plastic material) were used as the working medium for all photogrammetric measurements. The working diapositives with ground control, passpoint, and feature annotation are preserved. All the photogrammetric measurements reported by Krimmel (1992) and subsequent measurements were made by the author or people under his direct supervision. The methodology used for the photogrammetry was similar to that described by Meier and others (1985) with one major difference. The transfer of points (ground control and ice features) between different dates of photography that resulted in data described by Fountain (1982) and by Krimmel (1987), which included all the data referenced by Meier and others (1985), was made using different dates of photography on the respective sides of a stereo comparator with a floating point used for reference, and then marking the points with a 30-mm drill. Instead, for this photogrammetry the “different date” points transferred using a method of superposition. The rotationally oriented through-lighted and magnified diapositives were shifted relative to each other until surface patterns coincided, and then the similar feature was marked on both diapositives using a third basal layer marked with a reference point (equivalent to the floating point). The earlier method and this method used the same information, but in a somewhat different way. In this method the diapositives were marked with a carefully sharpened straight pin, leaving a pit about 100 mm in diameter. This method depended on diapositives of similar scale and of similar emulsion density, both of which could be manipulated during the photographic reproduction process when necessary.

Mistakes may occur. During the process of following features from date to date, feature pairs are matched on the diapositives for each of the two dates. If the respective feature identification is confused, displacements may show errors of several hundred meters or more. These mistakes are usually very evident when displacements are converted to vectors, and are then corrected. A mistake may also occur when what is thought to be the same feature on respective dates, in fact is not. This type of mistake may be as much several hundred meters, in which case it can easily be seen and removed; or a few meters or less, in which case it would make a contribution to measurement errors. The results were reviewed and obvious mistakes removed, but some may remain. Vectors that do not conform to nearby vectors should be suspect and may be removed from the data set. Mistakes are not considered to be errors.

Errors are inherent in photogrammetric methodology, and independently, in the identification of features in the sequential photography. An interior orientation corrects for systematic errors in lens and film distortion. A relative orientation corrects for earth curvature and refraction, and forms a 3-dimensional “model”. The models are joined using SIMBA (Olsen, 1975), a photogrammetric block adjustment package, and then tied to ground control in an absolute orientation which results in residuals that can be used to estimate the photogrammetric accuracy of measured points relative to the ground. The residuals typically suggest a photogrammetric accuracy of 2–4 m in both the horizontal and vertical for well-defined points. Additional error is introduced during the identification of the same point on different dates. The features change between the flight dates because of ablation or snow accumulation and deformation, and change in sun angle may give features a different appearance. A somewhat subjective accuracy of 3 m in location was assigned to a well-defined point, and 4 m to the length of a displacement vector (which requires two location measurements, and the identification of the same point).

The software that is used for the photogrammetry yields values to the millimeter. In many of the tables and associated files, insignificant digits are retained.

DATA ACQUIRED

Vertical aerial photography covering all or part of Columbia Glacier was obtained 119 times beginning in 1957 (117 times since mid 1976) until late 2000 (fig. 5, table 1). Nearly all of this photography was subjected to photogrammetric analysis, and whenever possible the terminus position, altitudes at some systematic grid of points, ice displacements from some previous photography date, area of glacier calved from the previous flight date, and the surface level of two ice-dammed lakes was measured.

Terminus Positions

Numerous points are measured at the ice/water contact along the terminus (table 2). The connection of these points is a map of the terminus configuration. The terminus is not always definable because in some photographs it is difficult to determine where the ice has separated from the glacier. In that case, points are picked subjectively to make a continuous terminus configuration. A selection of these terminus configurations is shown on figure 6. The terminus position is reduced to a single number to represent the glacier length on the particular date by width averaging it along the active ice front. This is a subjective task despite attempts to be objective (Meier and others, 1985, p. F16; Krimmel, 1992, p. 4) as the glacier has changed, subsequent objective width-averaging methods have become obsolete and new ones have been be devised. Since 1992 a consistent width-averaging method was not used, but rather a subjective determination of glacier length relative to the previous terminus position has been made, and with reference to the L points. The accuracy of the glacier length (table 1) is estimated to be 50 m, which is mainly because of contribution from the width-averaging system. Even with this large uncertainty, neither the long-term trend of a dramatically shortening (retreating) glacier nor the higher frequency length changes is lost (fig. 7).

Overlying the retreat trend is a cyclic length change in which advance is followed by greater retreat. This cyclic length change is assumed to be seasonally driven. A hand-drawn line though the time-length plot (fig. 7) approximates the length trend without the influence of the cyclic length change. This hand-drawn curve can be defined by x, y points along the line, producing a highly segmented line that can be subtracted from the measured lengths. The residual lengths, plotted as a function of the time of year along the abscissa (fig. 8) show a strong trend for a long (advanced) glacier in early summer, and a short (retreated) glacier in late fall or early winter. In an attempt to determine any change in the timing (within the year) or amplitude of the seasonal length change as the retreat has progressed, the residual lengths were divided into two periods: from 1975 through 1984, and from 1985 through 2000. A 4th degree polynomial, constrained to be periodic, was fit through both segments of values, which suggest that the time of maximum length has advanced from early June to early August, and the amplitude of the seasonal length change has increased by a factor of two.

Altitudes

Surface altitude is easily measured when the surface is fractured with crevasses or is otherwise rough. The height of a "point" is never measured, but rather the measurement is to a surface of finite area. The area of the surface measured is a function of the photography scale, plotter magnification, surface stereo fusion, and the photogrammetrist. Typically, the surface area included in a height measurement at Columbia Glacier is a circle with poorly defined outer limits and about 15 m in diameter. The surface roughness is averaged within that area. The height measurements are ordinarily biased toward the top of the seracs rather than some distance into the crevasses.

An advantage of stereo photography is that the determination of a complete altitude field is theoretically possible. A common 2-dimensional display of an altitude field is a contour map. No attempt was made to create contour maps from any of the Columbia Glacier photography described in this report. Instead, measurement of height was confined to predetermined specific X, Y locations. All measurements carry X, Y, and Z values, but the X, Y values always differ slightly from the X, Y of the nominally defined point locations. This variation in X, Y never exceeds the 15 m diameter "window", and does not alter the subsequent analyses of the height data. The nominal X, Y locations were designed to allow the creation of a time series of height change in important zones, or along the centerline of the glacier. In an attempt to reduce the effect of surface roughness and measurement inaccuracy, clusters of nearby measurements were sometimes averaged. The locations of features used to measure displacements (discussed in the next section) also carry a Z value that may also be used to determine the altitude field. However, the displacement features were not at consistent X, Y locations; thus it complicates analysis of the changing altitude field, and furthermore, these Z values were not specifically biased toward the serac tops.

Beginning in 1991, height measurements were made along transverse profiles at the L points (tables 3, 4; fig. 9). The transverse profiles consisted of 10 points spaced at 100 m on a line normal to the centerline. From 1983 to 1991 heights were measured at 100-m intervals in the east-west direction along UTM northings at 0.5 or 1.0 km intervals (Krimmel, 1992, p. 21–51). The 10 points of each of the 1991–2000 transverse profiles were averaged, and 10 points in nearly equivalent areas from each of the 1983–91 measurements were averaged, and results are plotted for L52 on figure 9. The long-term trend is for a thinning glacier. But the trend is by no means smooth—there are fluctuations within the thinning trend that are much larger than the measurement inaccuracies. The long-term thinning trend was removed by assuming that these fluctuations are driven seasonally and applying a method similar to that used with that glacier length time series (fig. 10). This suggests, but perhaps only marginally, that the glacier is thicker in early spring and thinner in the fall. The long-term height change over the entire length of the glacier is shown on figure 11. Near the receding terminus (wherever it may be) the height decreases about 20 m per year.

An area was picked where the ice had stagnated as the glacier retreated (shown as A on fig. 6). Within this area ice flow was negligible. A grid of 20 nominal X, Y points was established, and heights were measured on a series of late summer or early fall dates. The rate of change in the average height of all the points within the grid on each date represents the annual ice ablation (the net balance at that point) of about 9 m per year between 1983 and 1996 (fig. 12).

Displacements

In many areas the general appearance of the serac/crevasse patterns is preserved for several months, or even years, and is carried along with the flowing ice. Specific crevasses or seracs can be followed, date to date, and their locations measured on both dates. Depending mainly on the length of interval and region of the glacier, the density of displacement measurements may range from 1 to 20 per km2, with resulting vectors from a few meters to a few kilometers in length. An example of displacement vectors is shown on figure 13. The interval shown on figure 13 (August 13, 1994, to September 7, 1994) was short enough that displacements of icebergs in the brash matrix of the forebay could also be measured. The location of the measurements (table 5), that is, the end point of either end of the vector, was not consistent from flight interval to interval. Instead enough measurements were made so that displacements for specific locations could be interpolated from nearby locations. This interpolation was normally done using the derived speed vectors (table 6). As an example, interpolated speeds at L50 from 1977 to 1997 are shown on figure 14, where the large increase in speed over the time period is obvious. As with the terminus and the height data, the long-term speed increase can be removed, leaving speed deviations, separated into the periods 1977 though 1984 and 1985 through 1997, which are assumed to be seasonally cyclic. They are plotted on figure 15 and suggest high speed in spring and low speed in fall. Seasonal speed changes have continued this cyclic trend throughout the retreat, but with an increase in amplitude as the retreat has progressed. The fit curves on figure 15 are 3rd degree polynomials, not constrained to be periodic. The long-term speed change is plotted on figure 16.

The measurements that are used for displacements include a Z value, which may be useful for determining the vertical displacement of the ice, but those Z values are less reliable than those measurements made specifically for height.

Lake Levels

The water level of ice-dammed Terentiev Lake (adjacent to L62) and Kadin Lake (adjacent to L54) fluctuated during the terminus retreat through the forebay (see fig. 1 for locations). Few data exist prior to 1976, but presumably the lake levels were either stable or had periodic outbursts followed by refill to approximately the previous level. During the retreat both lakes had numerous outbursts, followed by subsequent refilling. By 1992 the Terentiev Lake level had stabilized at 13 m and will likely remain a freshwater lake, and by 2000 the Kadin Lake level had reached a low level of 15 m, but because ice still covered the outlet the lowest possible level is unknown. The fill-outburst cycles of both lakes had a lowering trend during the retreat, with a lowering of about 8.5 m per year (fig. 17).

Bathymetry

During the period when most of the speed and surface altitude measurements were made, the ice thickness and fiord bottom topography were unknown, or at best were inferred from radar (Brown and others, 1986) or modeling efforts (Rasmussen, 1989). Prevalent icebergs and compact brash ice in the forebay prevented the use of boat or helicopter-borne fathometers. In late summer or fall of 1995, 1996, and 1997 the forebay became mostly clear of floating ice, and a boat-borne fathometer was used to measure water depth at numerous discrete places to within a few hundred meters of the terminus ice cliff. No satisfactory explanation for the relatively ice-free forebay during those times is known.

A generalization of the bathymetry data is shown on figure 18, where contours are used to represent the forebay bottom. The contours were formed automatically using a 200-m grid formed using the Kriging method. Dots on figure 18 indicate the position of soundings. Users of these data should not rely on figure 18, but rather should refer to the entire bathymetric data set prior to any rigorous application.

Calving

The ice lost by calving at the terminus could sometimes be measured directly between flight dates. This required that the ice at the terminus on the second date be identified on the first date. This allowed the “ice-to-be-calved” to be surrounded by numerous points along the perimeter, that is, the top of the ice cliff at the terminus and an irregular line some distance up glacier from the terminus (fig. 19). This procedure was possible for most intervals from 1978–94. An example of an “ice-to-be-calved” file is shown in table 7.

The thickness of the “ice-to-be-calved” was taken as the average Z of all the perimeter points added to the average of all the gridded bathymetric values that were under the upper surface. The calved volume was taken to be the thickness times the number of 200-m grid points times 40,000 m2. Rate of calving is plotted on figure 20. The rate of calving has increased by a factor of 6 since the retreat began. The assumed seasonal cycle in the rate of calving is determined in a fashion similar to that of seasonal cycles in glacier length and speed, and if anything, is greater in the fall and reduced in the spring (fig. 21). The seasonal maximum rate of calving has tended to become later in the fall, with an increased magnitude between minimum and maximum rate as the retreat has progressed. The pre-1985 and post-1986 curves (fig. 21) are both unstrained 3rd degree polynomials.

DATA FILES AND STORAGE

The fundamental data are the photographic negatives. Data extracted from the stereo photography are preserved on optically readable medium, that being a CD-ROM formatted for MS Windows operation systems, a copy of which is included with this report. All files, except for images and the report text, are space-delimited ASCII. Any software capable of importing an ASCII text file should be able to read these files. No software is included in this report or on the CD-ROM.

All files are in one directory. The file names describe the file contents, thus it is important that files are not renamed without first somehow identifying the contents. Files were named with no systematic use of letter case. In the originating operating system (MSDOS) the letter case was ignored. Some operating systems may require a specific letter case, which may be determined by trial. The file structure, content, and names evolved though the period of this work and no attempt was made to improve upon these (other than to assure consistency). The stereo plotter software gave a line-by-line output that included four values: an integer identification which could be manually set, a real x, a real y, and a real z. The integer identification was retained even when it is meaningless.

Files with names of the form nnnT, where nnn is the flight number, contain terminus position data. Each file is in the form: C1 = an integer value of no use, C2 = a real value of UTM X, C3 = a real value of UTM Y, and C4 = a real value, usually near zero, of little use. Table 8 lists these files. No file exists for flight 078 because photogrammetry was never done on this flight, which was 2 days after flight 077, or for flight 110 because the quality was poor. Files for flights 075 and earlier are identical to those of Fountain, 1982, and Krimmel, 1987 and 1992.

Files with names of the form nnnP (table 9), where nnn is the flight number, are surface altitude data along profiles that also appeared in Krimmel, 1992 (Appendix 1). Each file is in the form of: C1 = a three or four digit integer number. The three digits, or if a four digit number, then the first three digits, is the central three digits in the seven digit UTM northing. If there is a fourth digit, a “1” indicates that the point is at the east or west end of the profile; if the fourth digit is a “0”, it is a point along the profile but beyond the edge of the glacier. C2 = UTM X, C3 = UTM Y, and C4 = Z.

File KMALT is a large file and includes all the altitude data taken at the specific profile points (table 3 is an example of the points). In this file C1 = flight number, C2 = UTM X, C3 = UTM Y, and C4 = Z. Table 9 gives the flight numbers for which these data were taken, and the number of points on each of those flight dates. For some dates and profiles redundant data exist because the same profile was measured on adjacent stereo models. Table 4 is a sample of these data.

Files with names of the form aaaV-bbb, bbbV-aaa (table 10), where aaa and bbb are the flight numbers, contain positions of points used for displacements; aaa is the number of the first flight and bbb is the number of the second flight. A few of these file names carry a single letter extension that is used when additional flight lines (for instance, for additional coverage or at a different scale) are flown on the same day and carry the same flight number. Table 5 is a portion of one of these files to show a sample of the file contents. Each file is in the form: C1 = an integer value that identifies the point, the equivalent point number is used in the subsequent (or preceding) flight, C2 = a real value of UTM X, C3 = a real value of UTM Y, C4 = a real value of Z. These files always occur in pairs; for instance, file 085V-086 contains the first location of points used to measure displacements from flight 085 to 086 and file 086v-085 contains the second location of points used to measure displacements from flight 085 to 086. The flight numbers, are usually, but not always, consecutive. Files with names of the form Gnnn, where nnn is a flight number are of points used for displacement prior to flight 036 and are of the form: C1 = a integer giving a point identification that is unique to a particular point from the first date on which it is located until it was no longer found on subsequent flight dates. When a point is lost, the same number may be used again on later dates. C2 = a real value of UTM X, C3 = a real value of UTM Y, and C4 = Z. Files for flight 075 and earlier are identical to those of Fountain, 1982, and Krimmel, 1987 and 1992.

Files of the form Vaaa-bbb (table 11), where aaa and bbb are the flight numbers, contain velocity data for the indicated interval. Table 6 is a portion of one of these files as an example of the file content. These data are derived from the respective pairs of aaaV-bbb and bbbV-aaa files. The file columns are defined in table 6. A few of these file names carry a single letter extension which is used when additional flight lines (for instance for additional coverage or at a different scale) flown on the same day and carry the same flight number. These velocity data are presented to demonstrate the high ice speeds at Columbia Glacier. Users of these data may wish to derive their own velocity files, in different formats or with different output, from the respective displacement files.

Files of the form nnnC (table 12), where nnn is the flight number, are “ice-to-be-calved” files. The flight number is the first of the pair of flight dates required. The interval is always to the next flight, but with one exception: file 077C is the “ice-to-be-calved” from flight 077 to flight 079. Table 7 is a portion of one of these files as an example of the file content. Each of the nnnC files is in the form: C1 = an integer value of no use, C2 = a real value of UTM X, C3 = a real value of UTM Y, and C4 = a real value of Z. These X, Y points form the perimeter of the “ice-to-be-calved” (see fig. 19). The Z values are measured to an average upper ice surface.

Files KMPTS, ABLATION, LKLEV, BATH, BATHGRID, CONTPTS, and CAMFILES are one of a kind, and are described in the next paragraphs. Each of these files contains header information describing its contents.

File KMPTS contains the nominal point locations for the altitude profiles used beginning in 1991 (the locations of altitudes given in file KMALT).

File ABLATION is the ice surface level in a stagnant ice area (box A on figure 6) on several dates.

File LKLEV is the surface level of Terentiev and Kadin Lakes.

File BATH contains all the bathymetric measurements from Columbia forebay.

File BATHGRID contains the bathymetric measurements from BATH gridded to a 200-m grid using a Kriging method.

File CONTPTS contains the ground control used in the photogrammetry.

File CAMFILES contains all available camera calibration reports used for the photogrammetry discussed in this report. Individual calibration reports (table 1) may be extracted from this text file. Table 1 references a calibration report for each flight.

The files with an extension of .tif are similar to the cover photograph and figures 2–4. File TEXT.doc is a MS word file containing the text of the report.

OTHER SOURCES FOR THESE DATA TYPES

Terminus position may be recorded by any good observer with a good vantage and camera. Commercial air traffic routes offer pilots and passengers good views of the terminus of Columbia Glacier on days with clear weather. Charter and private aircraft are also frequently in the vicinity of the terminus. Certainly many photographs exist that would serve to help map the terminus between the times of the vertical photography described in this report. No solicitation for such photographs were made, nor were the USGS files perused for random photographs of this type.

Space-borne radar, which has capability of observation when clouds prevent visible light viewing and during dark, often has resolution sufficient to show the terminus position of Columbia Glacier, but no effort has been made for this report to find the existing imagery. The Landsat series of satellites is restricted to observations during daylight and fair weather and also has sufficient resolution for useful terminus recording. The early Landsats were with a 80-m pixel, and of limited use at Columbia Glacier. With the advent of 30-m pixel size, or 15-m with Landsat 7, the terminus can easily be mapped. An exhaustive search for available satellite data was not intended, but a portion of a 1978 image from the short-lived Return Beam Vidicon Sensor (fig. 2) and one Landsat 7 image (fig. 3) were included.

CONCLUSIONS

Aerial photography and subsequent photogrammetric measurements have proven to be a very practical method to obtain extensive data concerning the static and dynamic geometry of Columbia Glacier.

Although it is not the intent of this report to determine processes that cause these changes in Columbia Glacier, I will go beyond a presentation of raw and condensed data and point out possible causes of some of the observations.

Changes in the terminus position (the glacier length) are an easy observation to make but are not an important consideration in the process of the changes, but rather, are only a consequence of speed and calving. The seasonal changes in glacier length are a result of seasonal changes in speed and calving.

Feedback from the terminus position may be important to the dynamics, if for instance, changing length resulted in changing basal drag. Likewise, changing height is a consequence only of changing glacier length—the mechanical properties of ice do not allow a terminal ice cliff several hundred meters high. The seasonal changes in height are caused by winter snow and summer ablation, or possibly dynamics effects. Feedback from the changes in ice thickness may be important because of resulting changes in pressure on the bed. The thinning of the glacier in the active areas (20 m or more per year) is much greater than in stagnant areas (9 m per year). Ice ablation rate (see fig. 12) and the general trend of the lowering of Terentiev and Kadin Lakes (see fig. 17) were all very similar to each other, suggesting a simple ice thickness control of the lake levels. Ablation area thinning from 1957–74 was a few meters or less, which suggests that the glacier was in climatic equilibrium for at least 2 decades prior to the onset of the rapid retreat: that is, the ice emergence term nearly matched the net balance.

This data set is large and complex. In its purest form it can be reduced to the original film negatives. The negatives represent the condition of the glacier at an instant in time, and of course, the time series of negatives represents a time series of the glacier conditions. By adding photogrammetric analysis of this photographic record, the time series can be described numerically. Only a small portion of the information that is inherent in the photography has been extracted. Additional displacement data, and particularly additional height data, could be extracted, perhaps best by the automated methods that have come into use in the 1990's. Interpretations made here are not intended to be the "last word"—new and better interpretations may be made and are welcomed. For example, a different approach to the width-averaging problem could result in a significantly different length-time function and suggest new retreat mechanisms; or by resegmenting the time-dependent length, height, speed, and calving records, different shifts in the assumed seasonal patterns and amplitudes may become evident.

This photographic record is the longest and most detailed that exists for any tidewater glacier, and because we cannot revisit the past, but rather rely only on records from the past, will become more valuable as it ages. If Columbia Glacier ultimately retreats through its fiord completely, and the fiord bed is mapped, then future generations of glaciologists will have a rich data set of glacier geometry and dynamics to model. It is my hope that this photographic data set and data in this report, or additionally extracted data, will be the impetus for that use, and may play a part in answering major questions concerning past, present, and future ice sheet stability.

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FIGURES

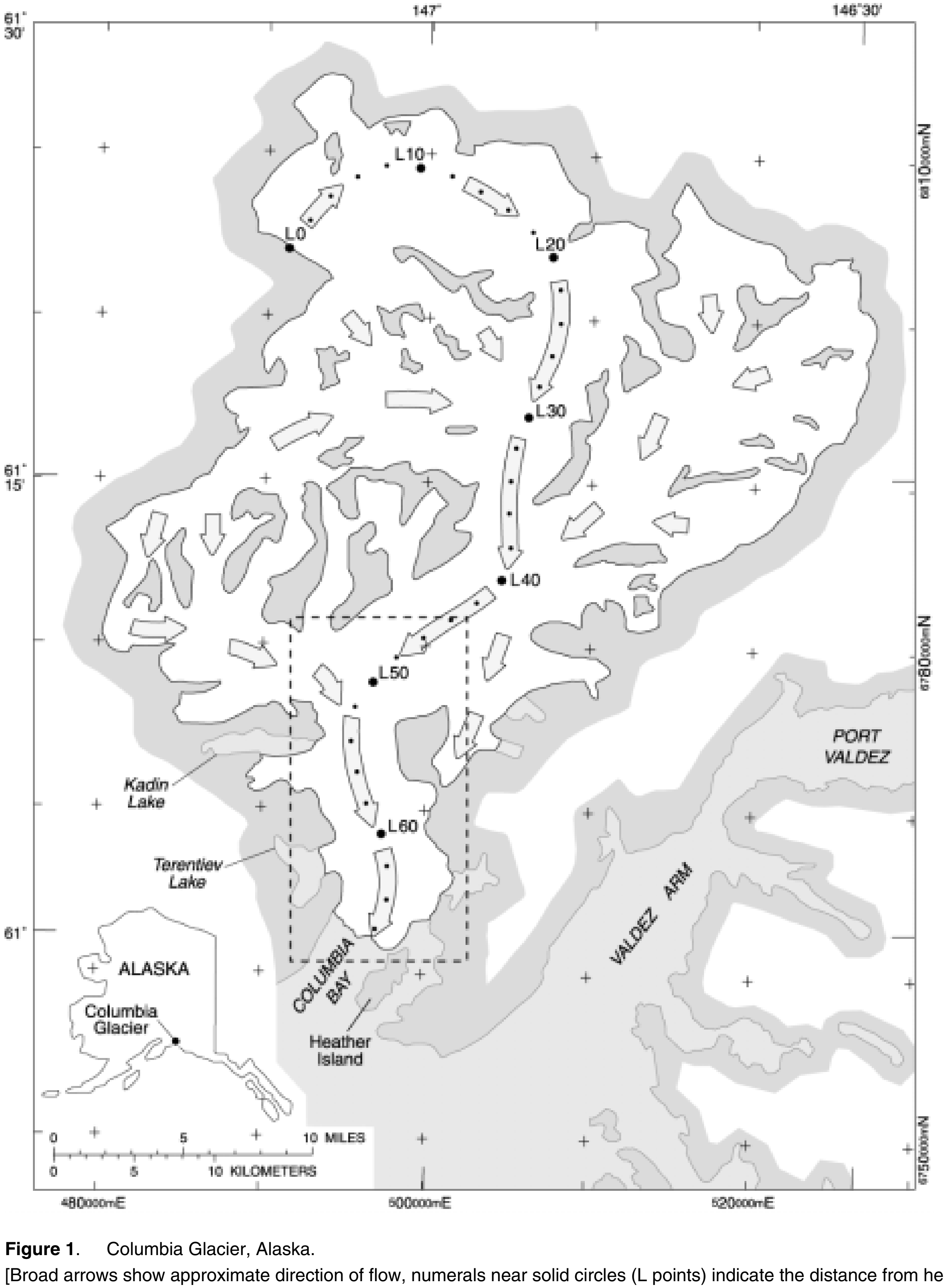

Figure 1. Columbia Glacier, Alaska.

[Broad arrows show approximate direction of flow, numerals near solid circles (L points) indicate the distance from head of glacier along the centerline, in kilometers, dashed box indicates the lower reach area over which the aerial photography was concentrated.]

Figure 2. Columbia Glacier as imaged by Landsat Return Beam Vidicon (RBV) on August 26, 1978.

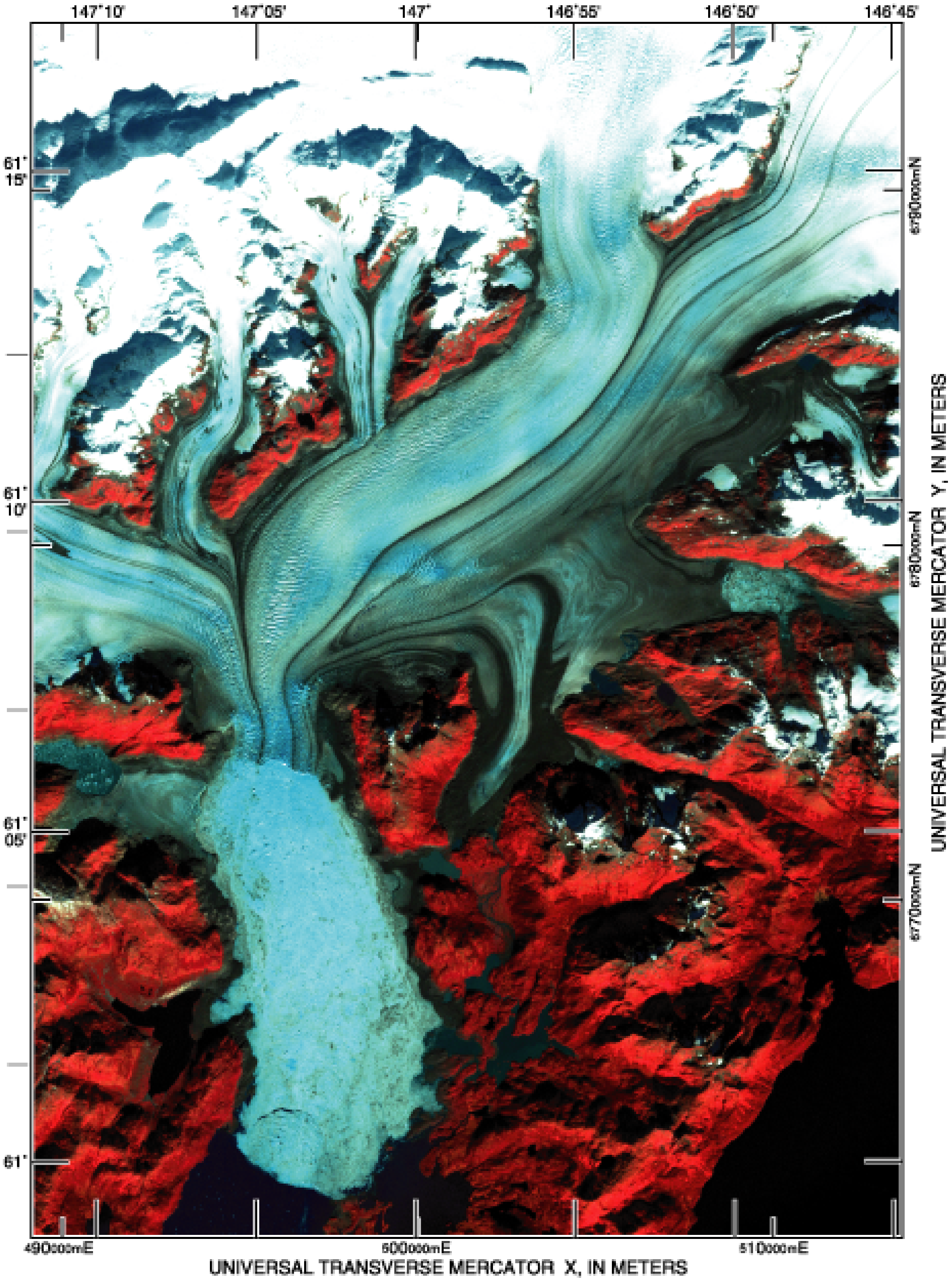

Figure 3. Columbia Glacier as imaged by Landsat Thematic Mapper (TM) on September 26, 1999. Vegetation appears red in this false color band combination. Note the change in the medial moraines between 1978 (figure 2) and 1999 near the image center.

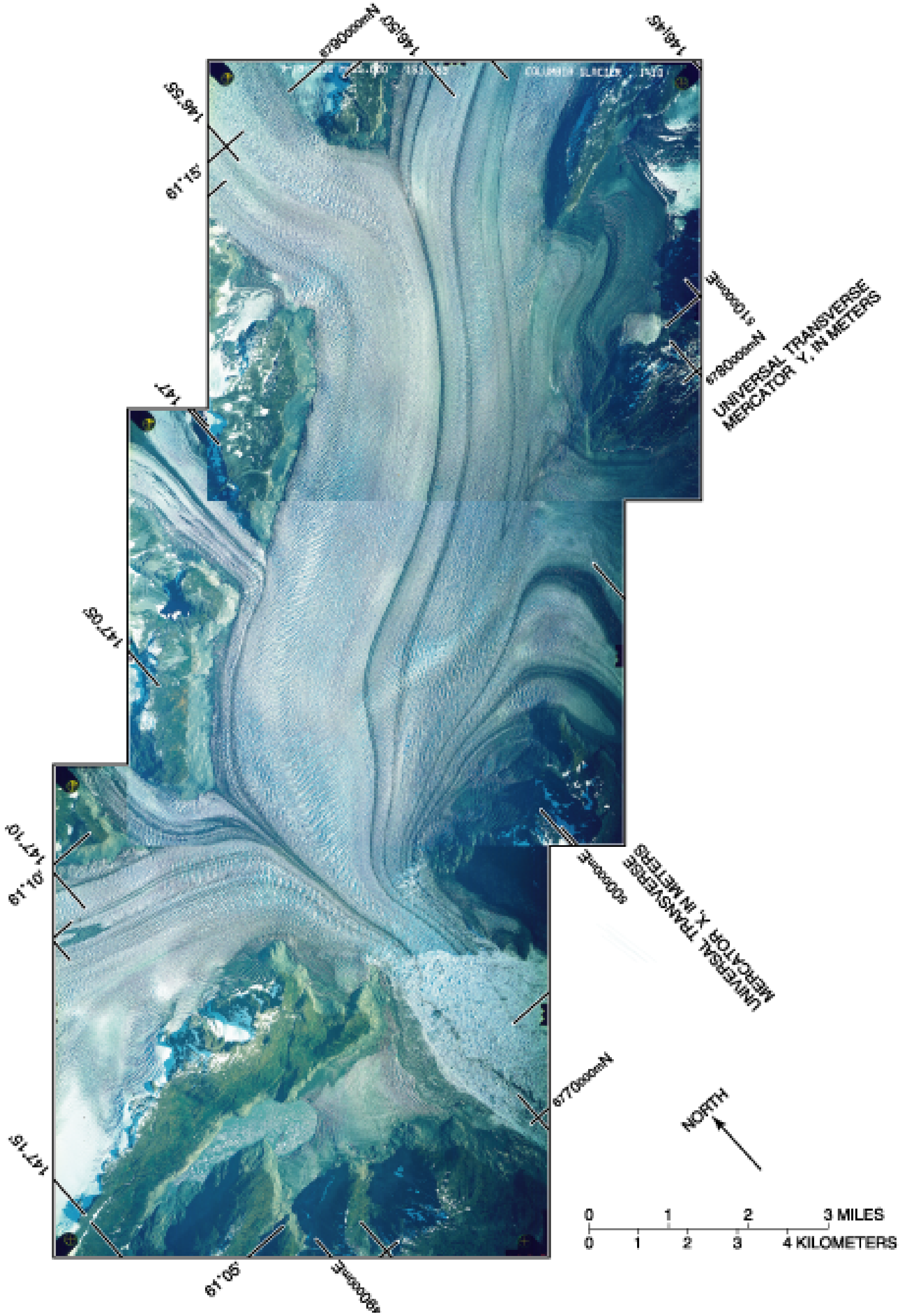

Figure 4. Vertical photographic mosaic of a portion of Columbia Glacier, September 18, 2000

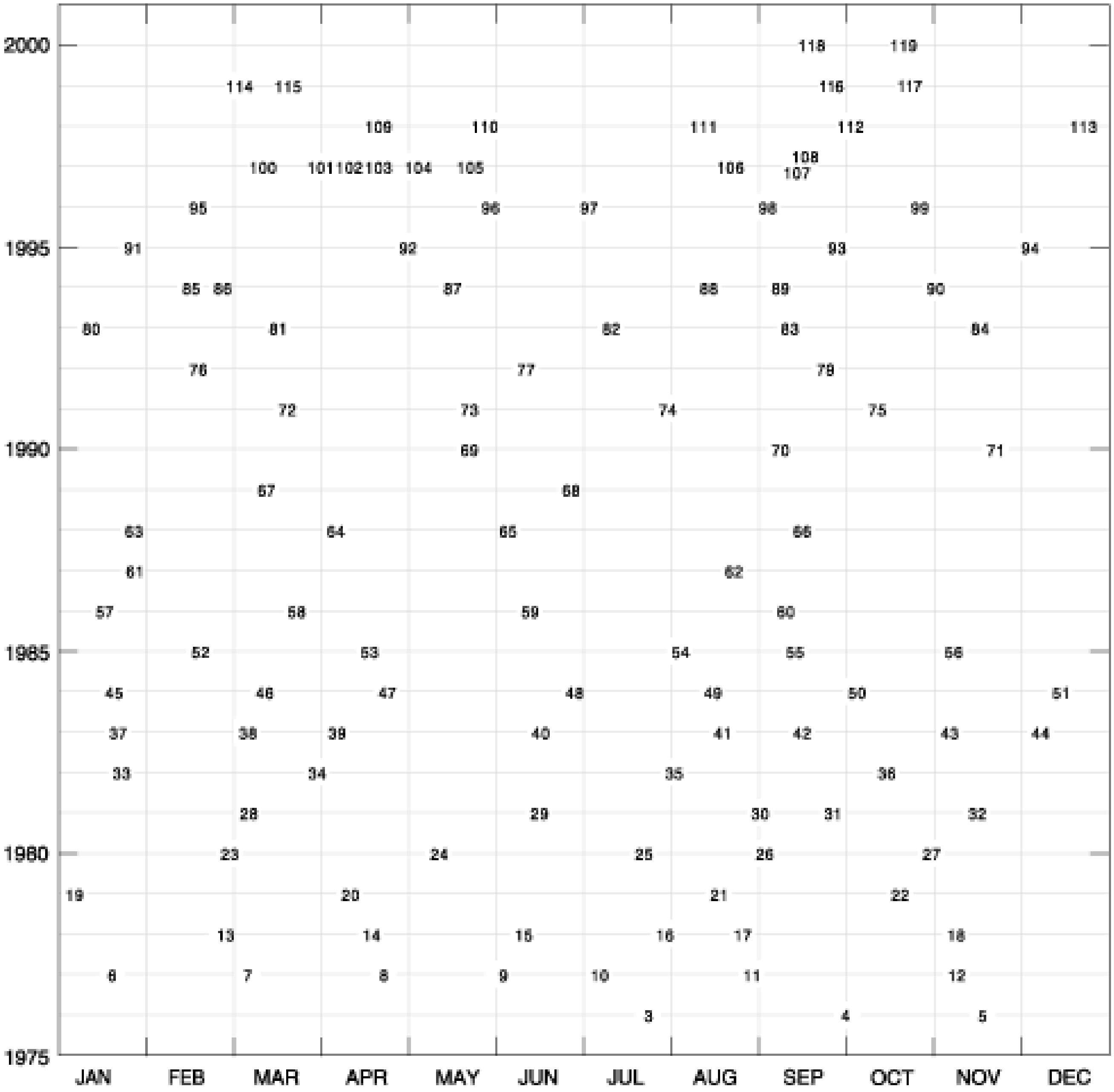

Figure 5. Columbia Glacier vertical photography flights.
The flight numbers are shown at the time within the year indicated along the abscissa.

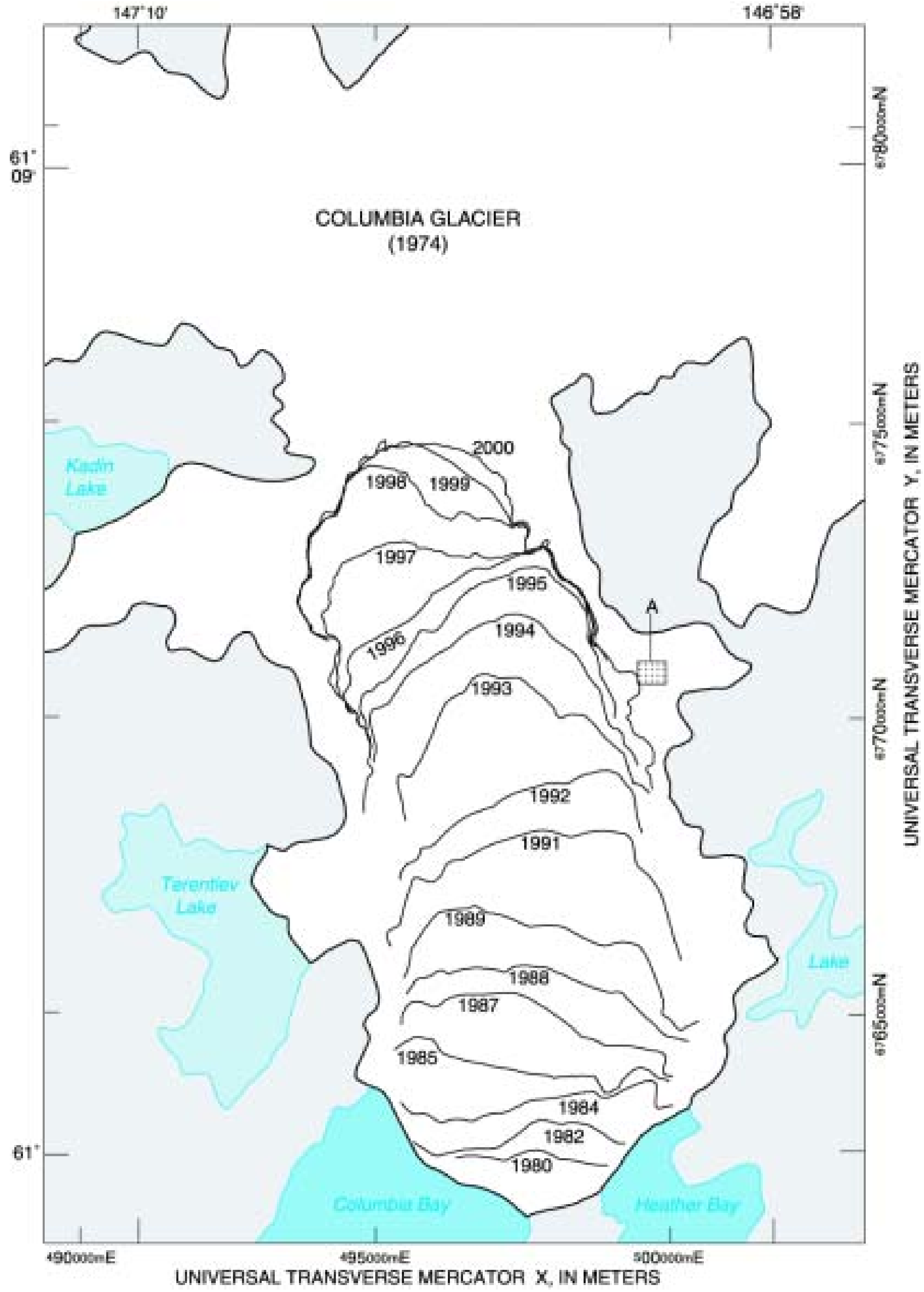

Figure 6. Selected Columbia Glacier terminus positions from 1974-2000. Box A indicates the area used in an ablation study. Glacier outline is from 1974.

t

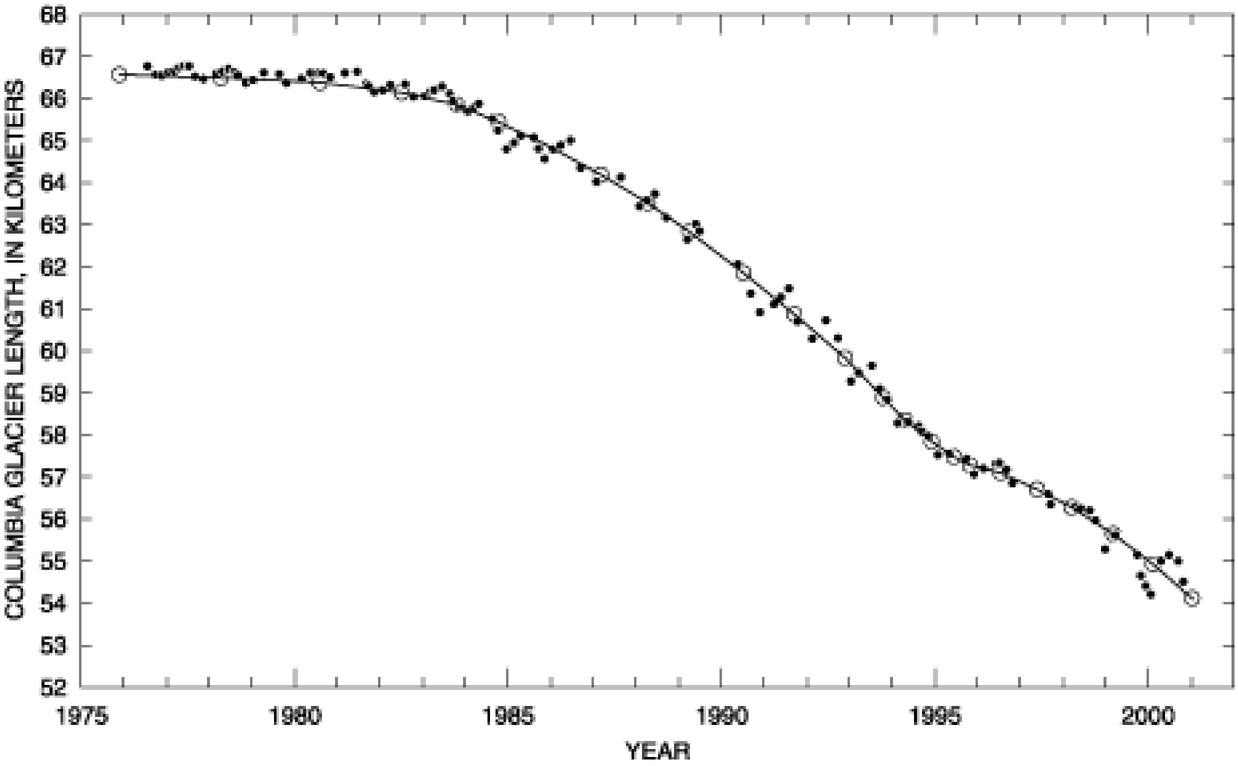

Figure 7. Columbia Glacier width-averaged length from 1976-2000.

The solid circles indicate the length and the open circles are points along the indicated hand-drawn curve. Year ticks indicate January 1.

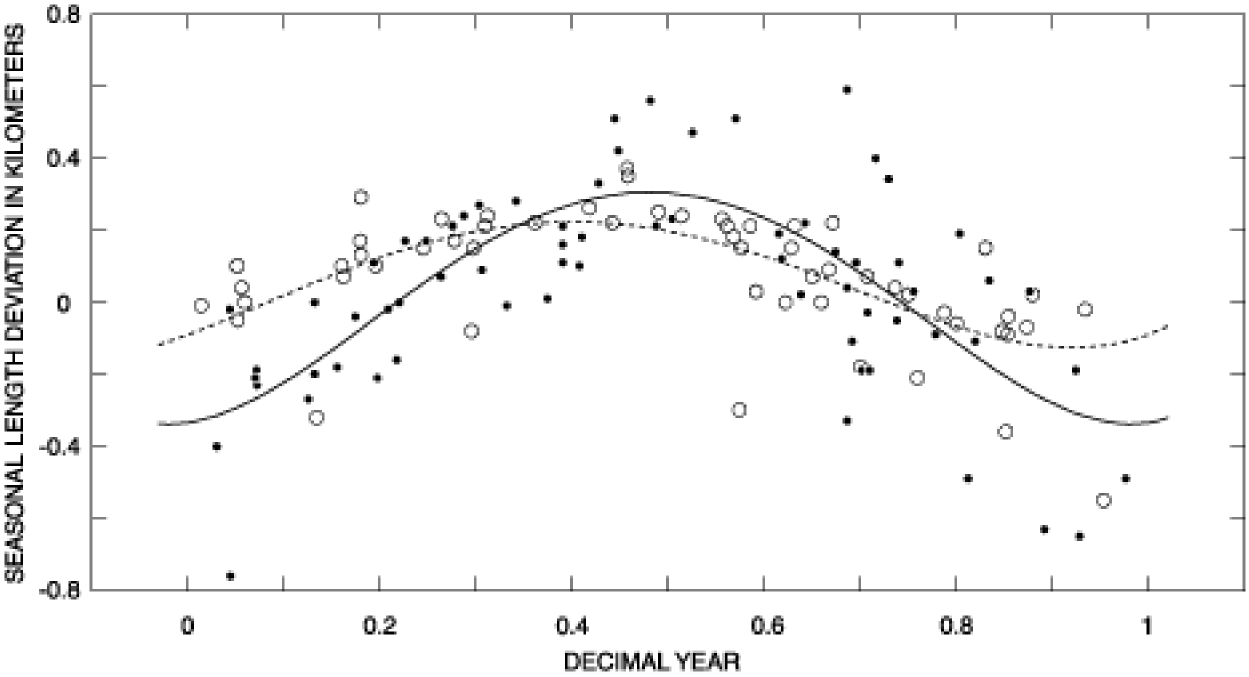

Figure 8. Seasonal deviations in the length of Columbia Glacier, as measured from the hand-drawn curve shown on figure 7.

The length deviation for each flight date is shown on the ordinate, the time of year for each flight date is shown on the abscissa. Circles are for flights from 1875-84, dashed line is the fit curve (r^2=0.409). Dots are for flights after 1984, black line is the fit curve (r^2=0.516).

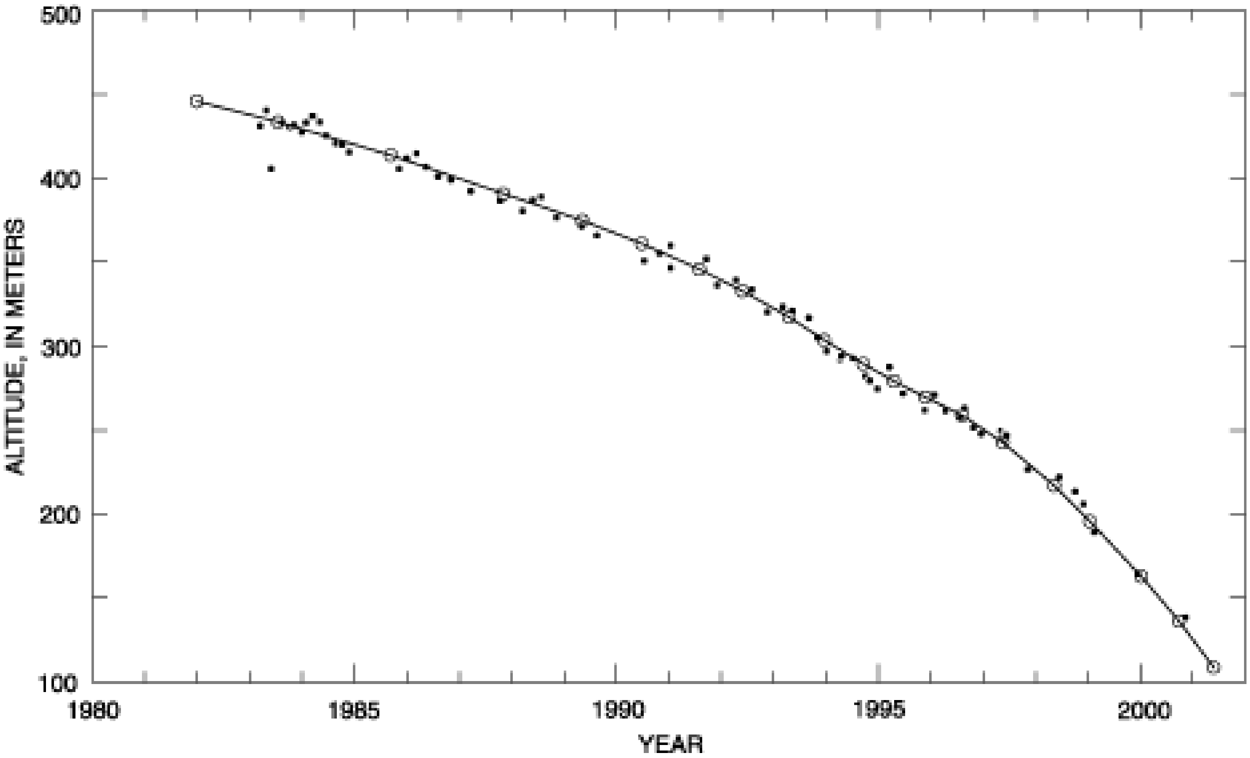

Figure 9. Columbia Glacier surface altitudes at L52 on flight dates from 1983-2000.

Solid circles indicate altitude on each date, open circles are points along the indicated hand-drawn curve. Year ticks indicate January 1.

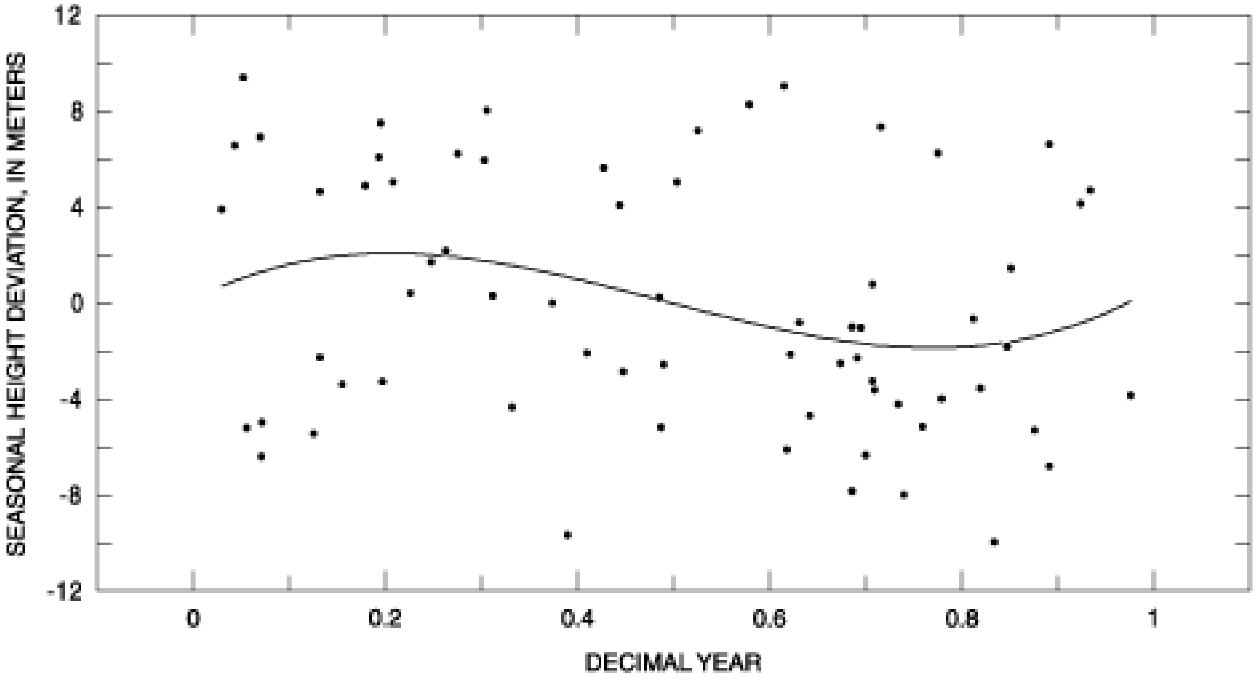

Figure 10. Seasonal height deviations at L52 on Columbia Glacier, as measured form the hand-drawn curve shown on figure 9.

The height deviation of reach flight date is shown on the ordinate, the time of year for each flight data is shown on the abscissa. The solid line is a 3rd degree polynomial fit through the points, and with an r^2 of 0.08 and may not be statistically significant.

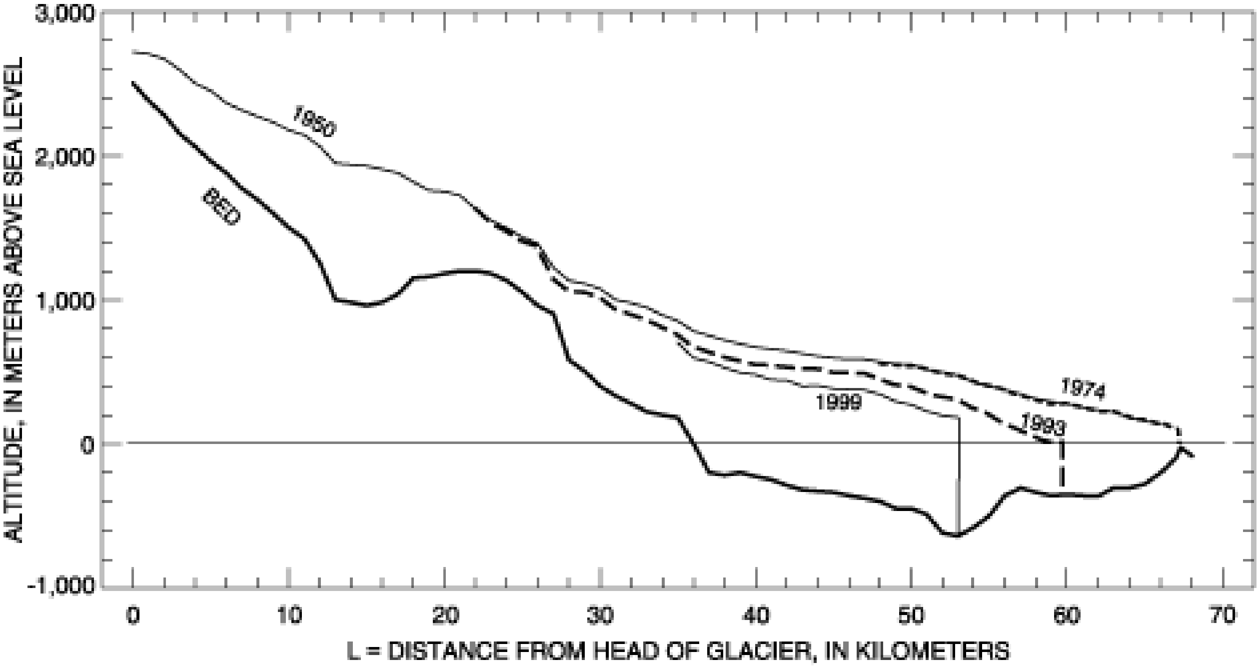

Figure 11. Height change of Columbia Glacier surface along the centerline.

The 1950 and 1974 profiles were nearly the same. By 1982, the surface began to depress rapidly. the bed is measured form L58 t0 L68, and estimated by modeling and a borehole along the remaining distance upglacier.

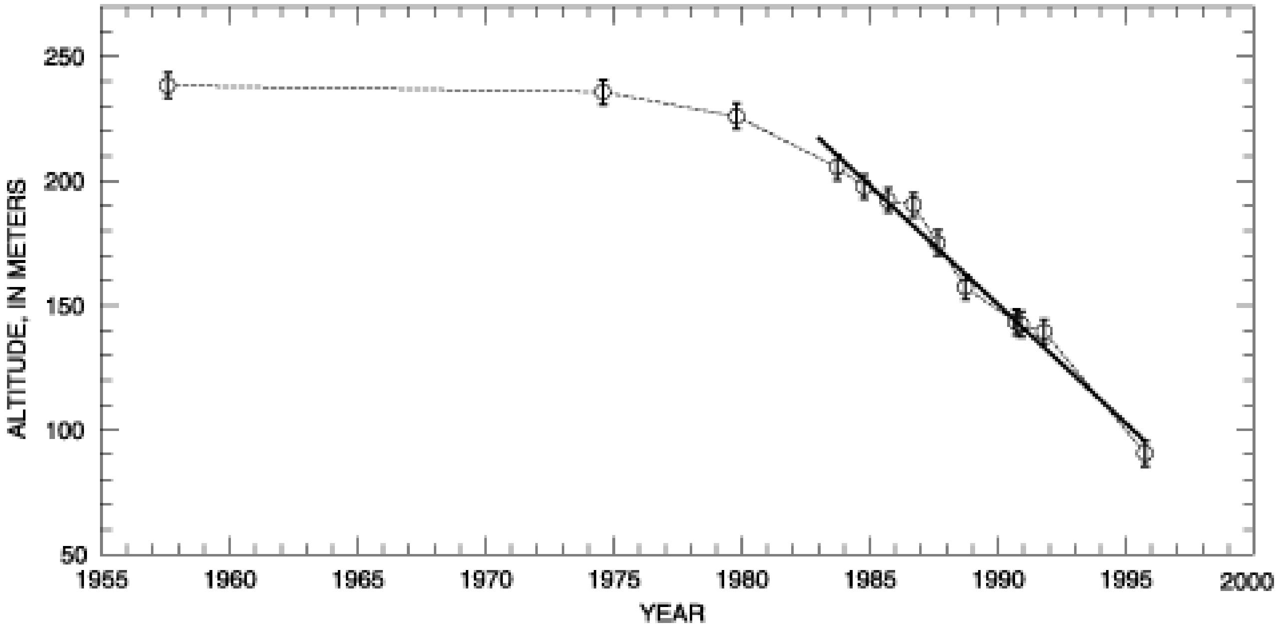

Figure 12. Surface lowering in a stagnant ice area of the lower Columbia Glacier.

Circles are averages of the points in a 20-point grid (A on figure 6) on each date measured. The heavy line is the linear trend after ice stagnation occurred. year ticks indicate January 1.

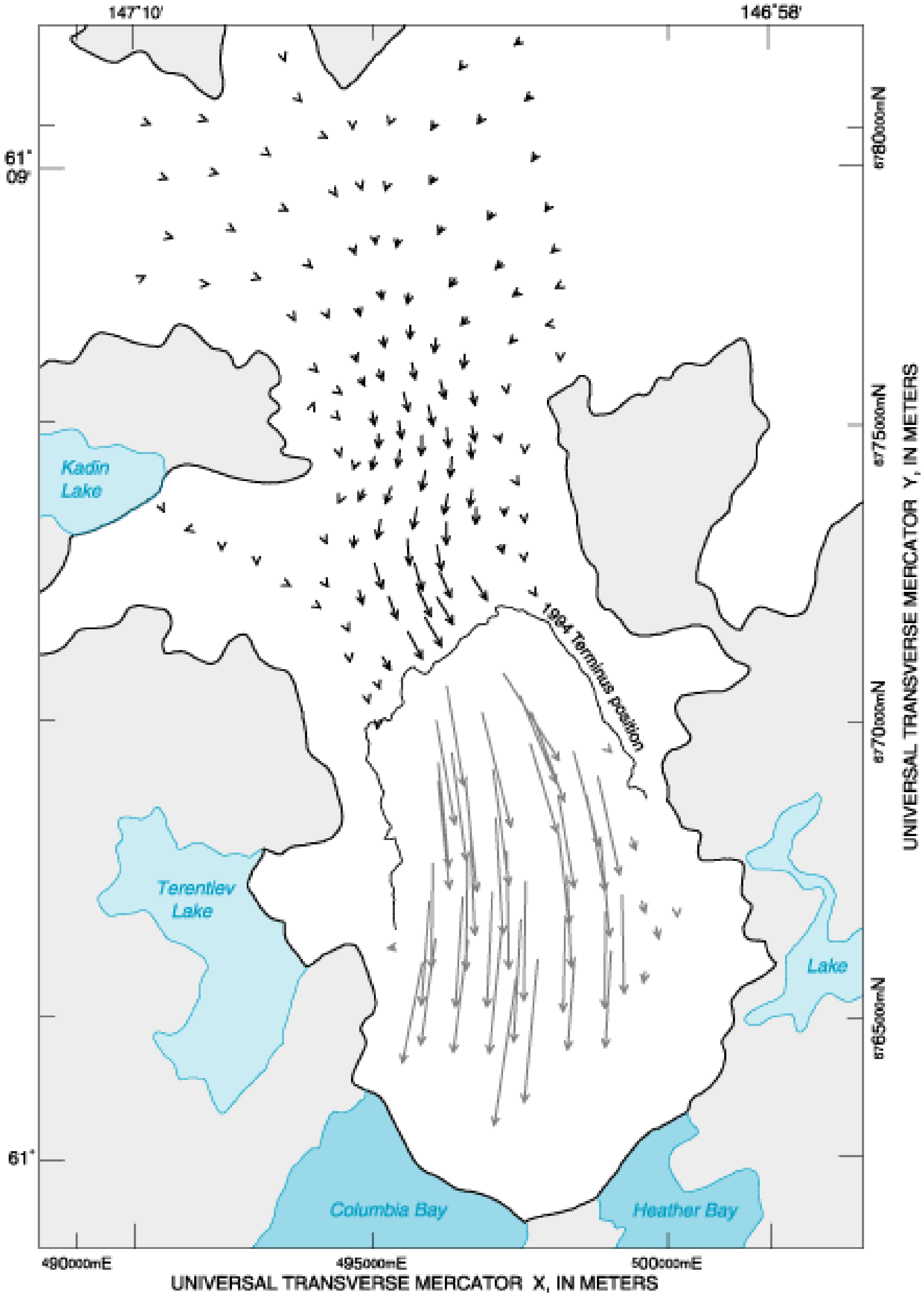

Figure 13. Columbia Glacier surface displacements for the interval August 13 to September 7, 1994 (flights 88-89).

Arrow tail is at flight 88 position, arrow head is at flight 89 position. Arrows may show an erroneous direction when the movement was less than a few meters. Displacements in the forebay are that of the floating ice mass.

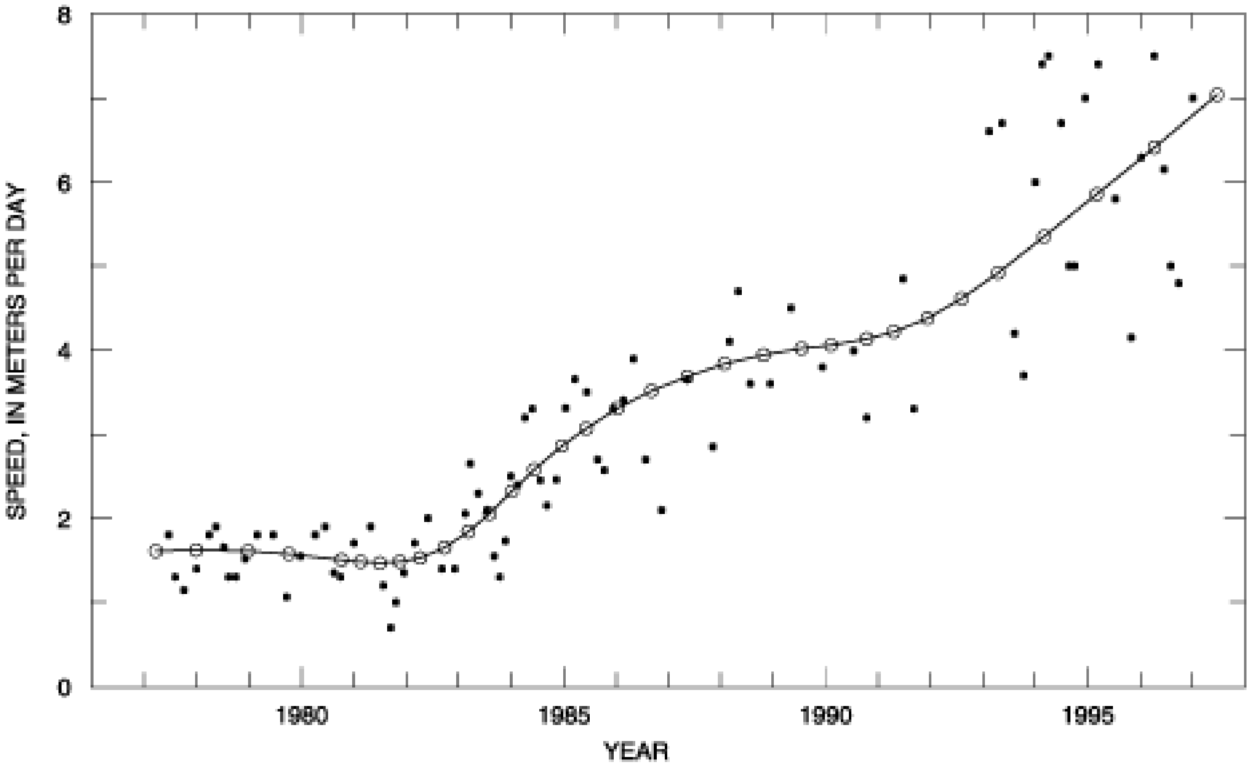

Figure 14. Speed at the L50 point on Columbia Glacier, 1977-97.

Solid circles indicate the speed during each flight interval, open circles are points along the indicated hand-drawn curve. Year ticks indicate January 1.

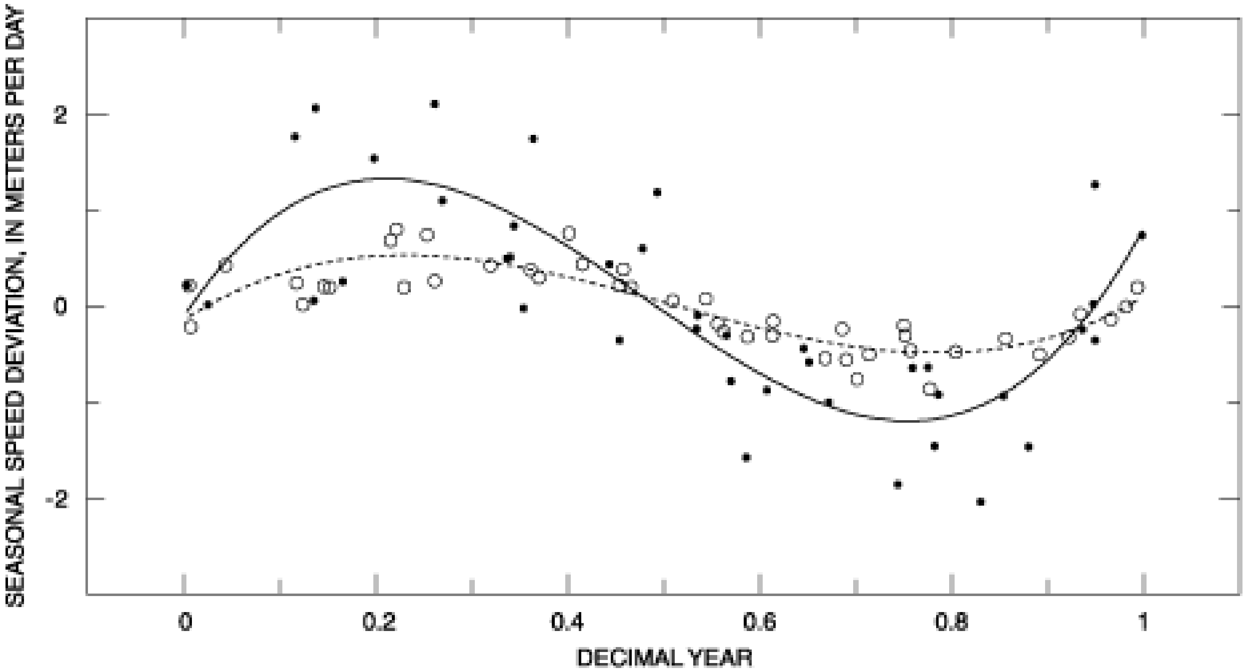

Figure 15. Seasonal speed deviations at L50, as measured from the hand-drawn curve shown on figure 14.

The speed deviation for each flight interval is shown on the ordinate, the time of year for each flight date is shown on the abscissa. Circles are for intervals from 1978-84, and dots are for intervals after 1984. The dashed line is a 3rd degree polynomial fit through the former points with an r^2 of 0.759 and the black line is a 3rd degree polynomial fit through the latter points with an r^2 of 0.670.

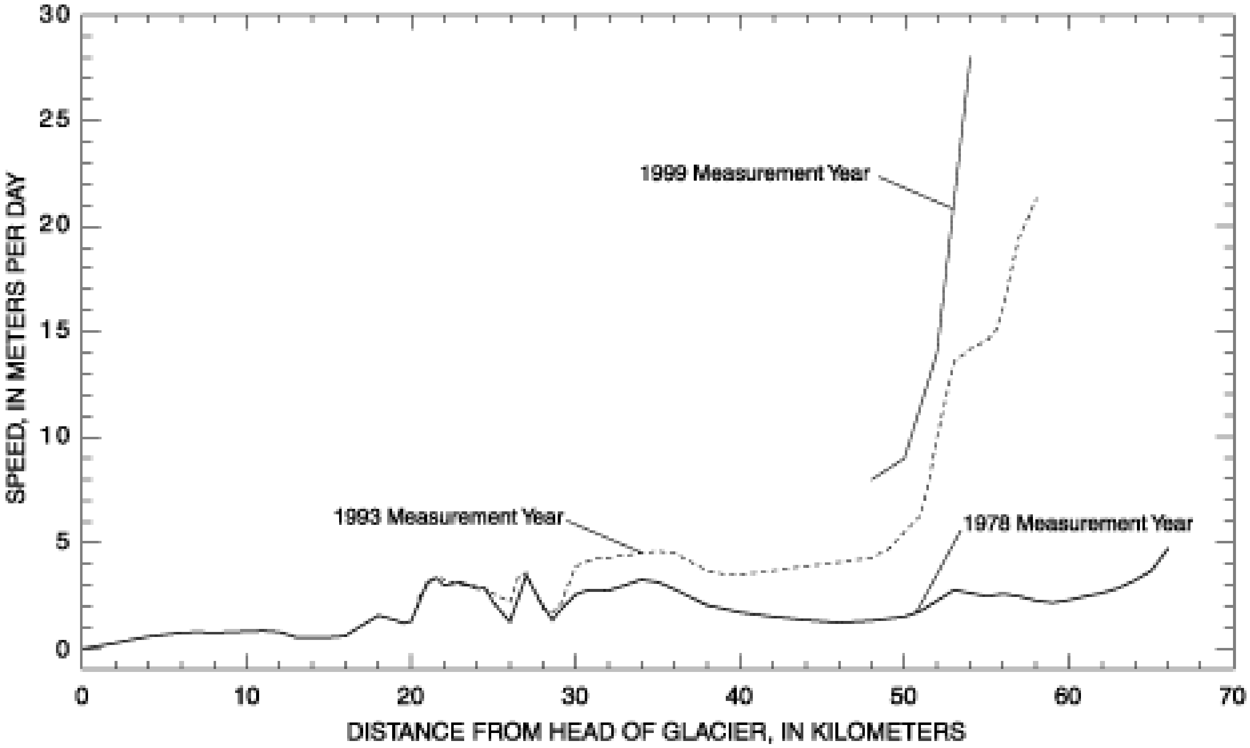

Figure 16. Annual speed of Columbia Glacier along centerline for measurement years (September through the following August) 1978, 1993, and 1999.

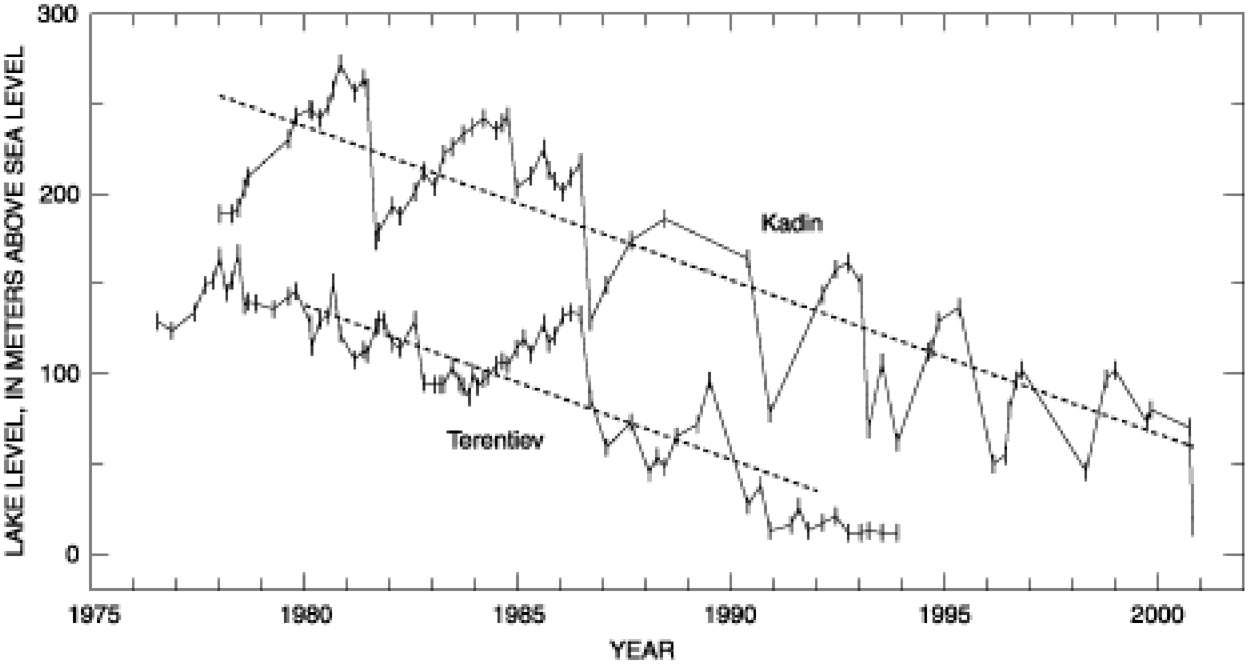

Figure 17. Level of Kadin and Terentiev Lakes near Columbia Glacier (see figure 1 for locations). The dashed lines are the linear trend over the years spanned by the line. Year ticks indicate January 1.

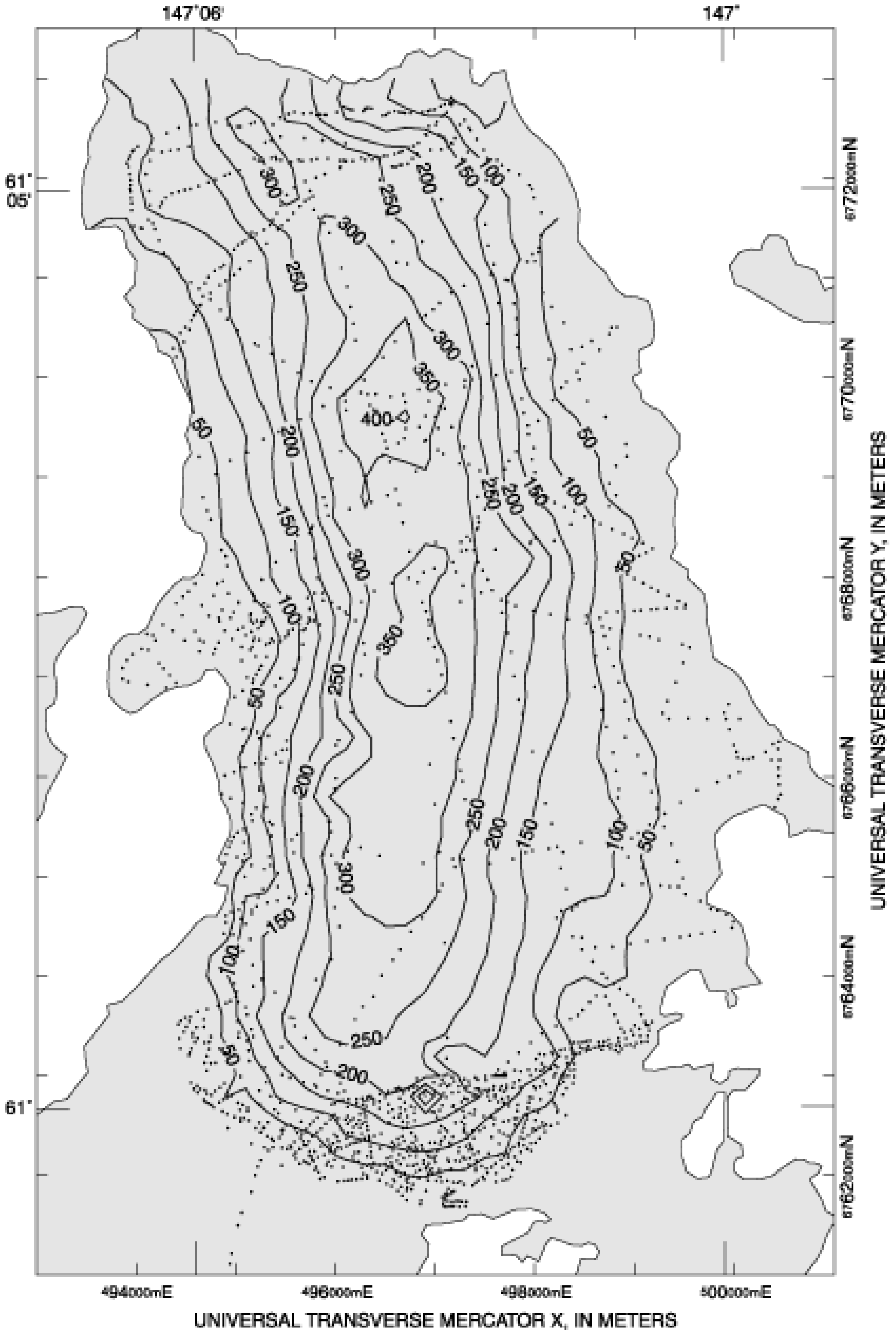

Figure 18. Bathymetric measurement locations and contours of water depth in Columbia Glacier forebay.

Each dot is a sounding location, the contours are in meters of water depth.

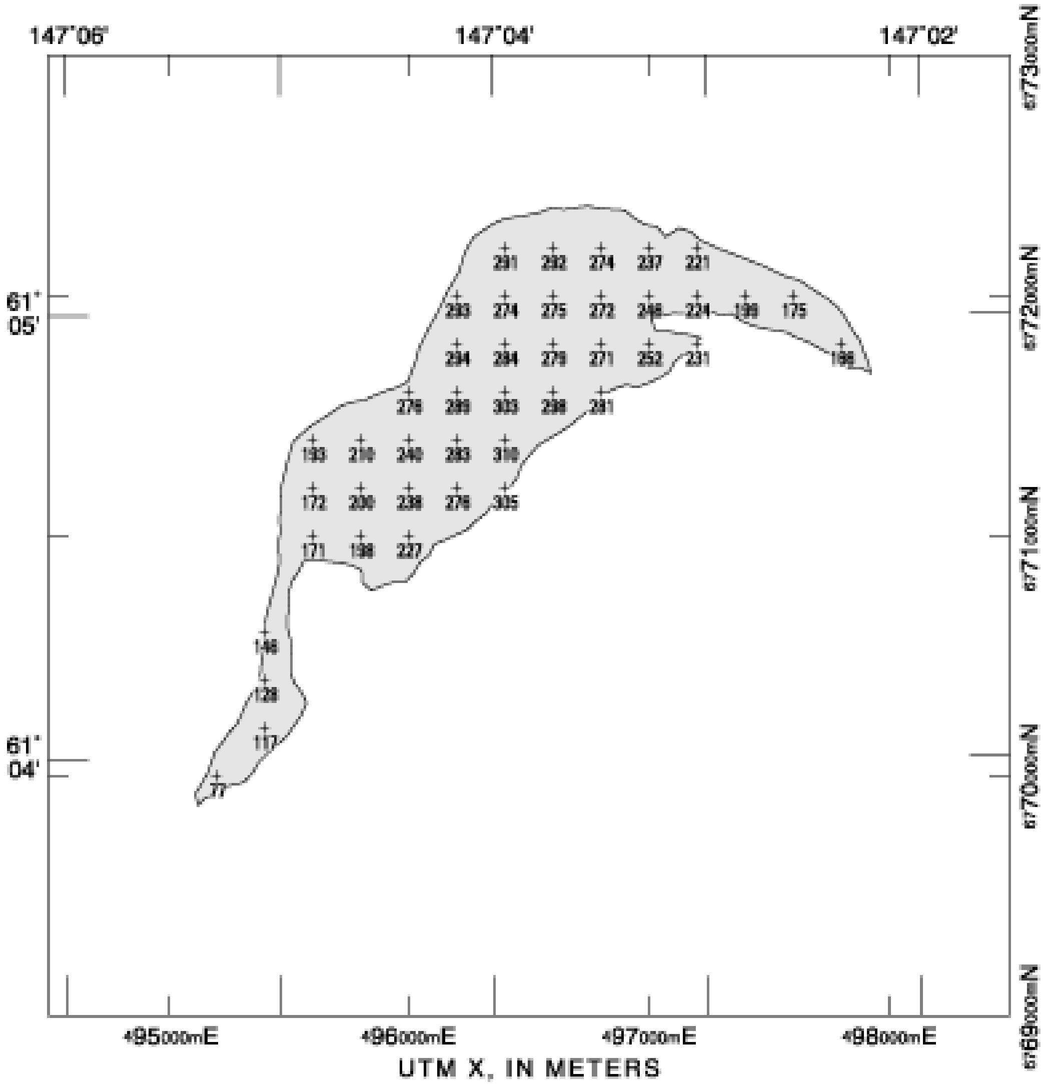

Figure 19. Columbia Glacier "ice-to-calved" for the epoch from August 13 to September 7, 1984 (flights 88-89).

The volume of "ice-to-be-calved" is taken as the area times the average of the gridded bathymetric measurements included within the area plus the average height of the surface perimeter points.

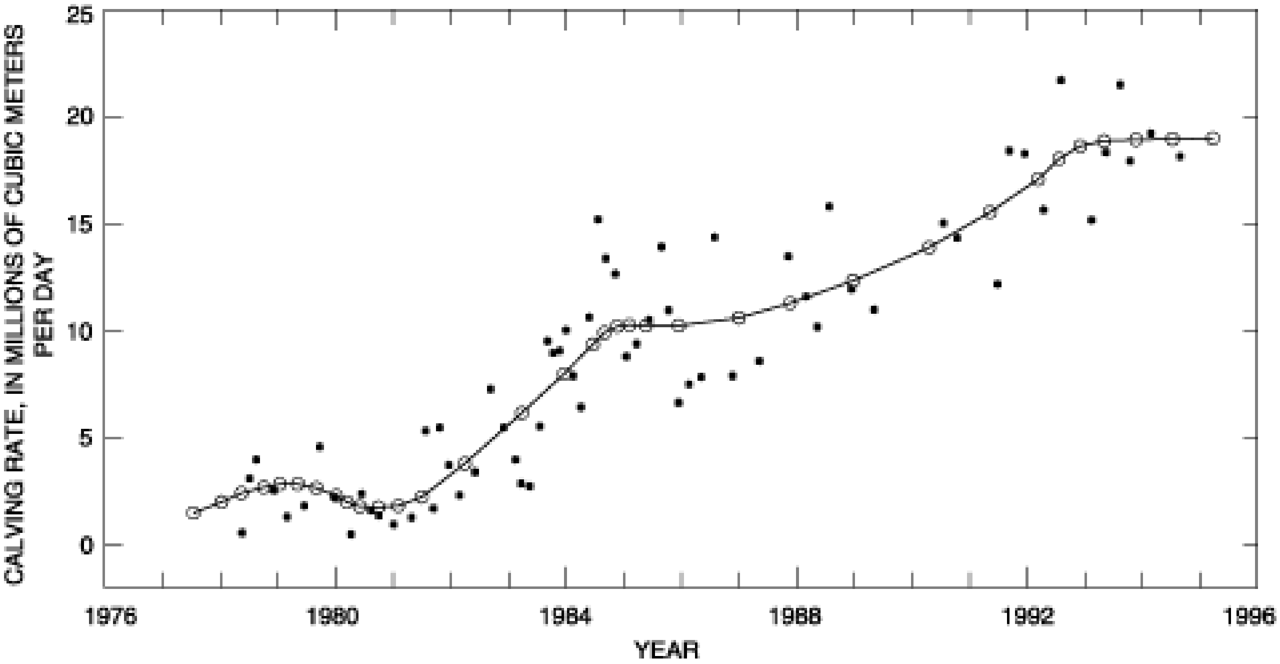

Figure 20. Calving rate at Columbia Glacier 1976-95.

Solid circles indicate the calving rate during each flight interval, open circles are points along the indicated hand-drawn curve. Year ticks indicate January 1.

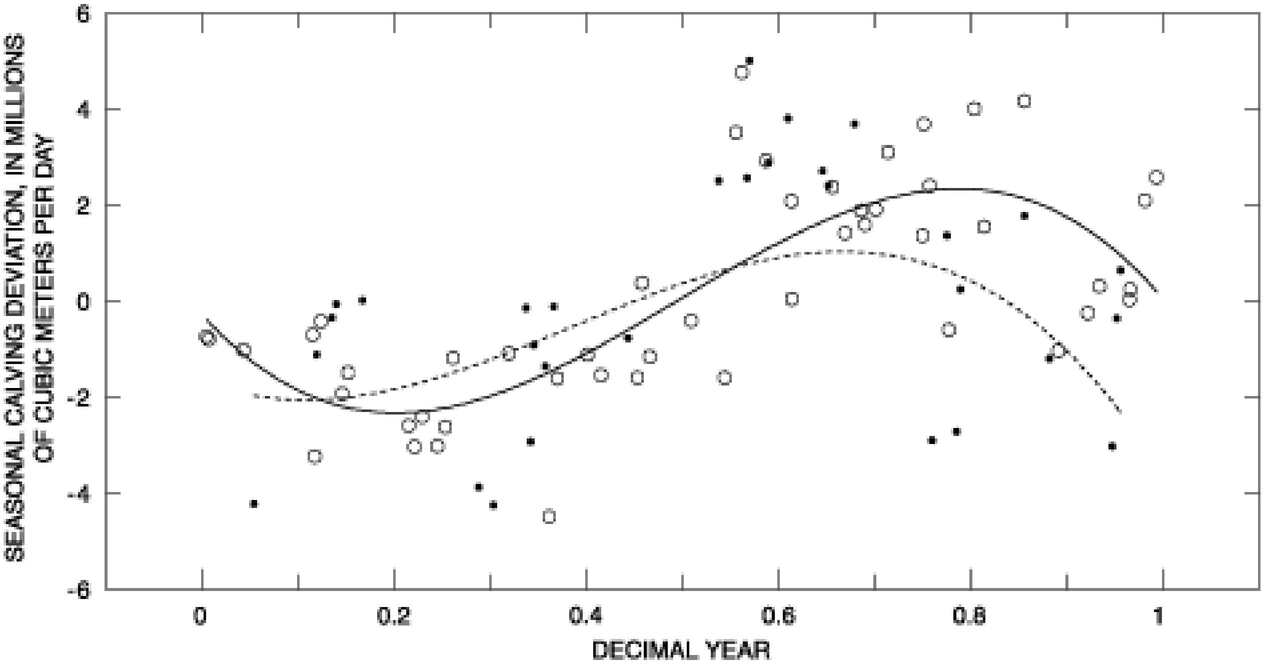

Figure 21. Seasonal calving rate deviations for Columbia Glacier, as measured from the hand drawn curve on figure 20. The calving rate deviation for each flight interval is shown on the ordinate, the time of year for each flight date is shown on the abscissa. Circles are for intervals from 1977-84, dots are for intervals after 1984. The dashed line is a 3rd degree polynomial fit through the former points with an r^2 of 0.158, and the black line is a 3rd degree polynomial fit through the latter points with an r^2 of 0.585.

Table 1. Columbia Glacier vertical photography flights
[m, meters; km, kilometers; UTM, Universal Transverse Mercator]

Flight number	Date	*t* Decimal year[1]	*D* day number[1]	Flight altitude(m), coverage, and quality[2]	Glacier length (km)[3]	Camera file[4]
001	29JUL57	1957.574	-7460	9,000 a	66.84	COL1958
002	27JUL74	1974.568	-1253	7,920 b	66.79	C54
003	24JUL76	1976.561	-525	5,490 c	66.75	C48
004	01OCT76	1976.750	-456	5,490 c	66.56	C48
005	17NOV76	1976.879	-409	5,490 c	66.55	C48
006	19JAN77	1977.051	-346	5,490 c	66.63	NMD13
007	07MAR77	1977.180	-299	5,490 c	66.65	C48
008	23APR77	1977.309	-252	5,490 c	66.73	C48
009	02JUN77	1977.418	-212	5,490 d	66.78	C48
010	07JUL77	1977.514	-177	7,010 d	66.75	C48
011	29AUG77	1977.659	-124	7,010 d	66.51	C48
012	08NOV77	1977.854	-53	7,010, 8,230 d, f	66.46	C48
013	28FEB78	1978.160	59	6,400 d	66.59	NMD13
014	19APR78	1978.297	109	7,010, 7,770 d, e, f	66.64	C48
015	11JUN78	1978.442	162	7,010, 7,770 d, e, f	66.70	C48
016	30JUL78	1978.576	211	7,010, 8,530 d, e, f	66.62	C48
017	26AUG78	1978.650	238	7,010 d	66.54	C48
018	08NOV78	1978.853	312	5,490 d	66.37	C48
019	06JAN79	1979.014	371	6,100 d	66.44	C48
020	12APR79	1979.277	467	7,010 d	66.61	C48
021	18AUG79	1979.628	595	7,010 d	66.57	C48
022	20OCT79	1979.800	658	7,010 d	66.36	C48
023	29FEB80	1980.162	790	7,010 d	66.47	C48
024	12MAY80	1980.361	863	7,010 d	66.61	C48
025	22JUL80	1980.556	934	7,010 d	66.61	C48
026	02SEP80	1980.671	976	7,010 d	66.59	C48
027	30OCT80	1980.830	1034	7,010 d	66.50	C48
028	07MAR81	1981.180	1162	7,010 d	66.60	C49
029	16JUN81	1981.457	1263	7,010 d	66.64	C49
030	01SEP81	1981.667	1340	7,010 d	66.34	C49

Table 1. Columbia Glacier vertical photography flights—Continued

Flight number	Date	*t* Decimal year[1]	*D* day number[1]	Flight altitude(m), coverage, and quality[2]	Glacier length (km)[3]	Camera file[4]
031	26SEP81	1981.736	1365	6,400 d	66.28	KC1B
032	15NOV81	1981.873	1415	7,010 d	66.15	C49
033	22JAN82	1982.059	1483	7,010 d	66.20	C49
034	31MAR82	1982.245	1551	7,010 d	66.32	C49
035	02AUG82	1982.585	1675	7,010 d	66.33	C49
036	15OCT82	1982.787	1749	7,010 d	66.05	C49
037	21JAN83	1983.056	1847	7,010 d	66.06	C54
038	07MAR83	1983.179	1892	7,010 d	66.16	C54
039	07APR83	1983.264	1923	7,010 d	66.20	BLM83-2
040	17JUN83	1983.458	1994	7,010 d	66.28	C54
041	19AUG83	1983.630	2057	7,010 d	66.10	C54
042	16SEP83	1983.707	2085	7,010 d	65.94	C54
043	06NOV83	1983.847	2136	7,010 d	65.75	C54
044	08DEC83	1983.934	2168	7,010 d	65.77	C49
045	20JAN84	1984.052	2211	7,010 d	65.69	C54
046	12MAR84	1984.195	2263	7,010 d, tp	65.78	C50
047	24APR84	1984.312	2306	7,010 d, tp	65.88	C50
048	28JUN84	1984.490	2371	7,010 d	65.81	C50
049	15AUG84	1984.622	2419	7,010 d	65.51	C50
050	04OCT84	1984.759	2469	7,010 d	65.24	C54
051	14DEC84	1984.953	2540	7,010 d	64.80	C50
052	18FEB85	1985.134	2606	7,010 d	64.95	C50
053	18APR85	1985.295	2665	7,010 d, tp	65.11	C50
054	04AUG85	1985.591	2773	7,010 d	65.07	C50
055	13SEP85	1985.700	2813	7,010 d	64.81	C50
056	07NOV85	1985.851	2868	7,010 d	64.56	C55
057	16JAN86	1986.043	2938	7,010 d	64.79	C50
058	24MAR86	1986.226	3005	7,010 d	64.88	C50
059	13JUN86	1986.448	3086	7,010 d	65.01	C50
060	10SEP86	1986.692	3175	7,010 d	64.35	C50
061	26JAN87	1987.069	3313	7,010 d	64.01	C50
062	22AUG87	1987.639	3521	7,010 d	64.12	C53

Table 1. Columbia Glacier vertical photography flights—Continued

Flight number	Date	*t* Decimal year[1]	*D* day number[1]	Flight altitude(m), coverage, and quality[2]	Glacier length (km)[3]	Camera file[4]
063	26JAN88	1988.069	3678	7,010 d	63.44	C53
064	05APR88	1988.260	3748	7,010 d	63.58	C53
065	04JUN88	1988.427	3809	7,010 d, tp	63.73	AMUSRC8
066	14SEP88	1988.704	3910	7,010 d	63.17	APTJENA4
067	12MAR89	1989.194	4089	7,010 d	62.65	APTJENA4
068	26JUN89	1989.484	4195	7,010 d	62.85	NOS88
069	22MAY90	1990.388	4525	7,010 d	62.05	Z1381
070	07SEP90	1990.683	4633	7,010 d	61.37	C51
071	21NOV90	1990.889	4708	7,010 d	60.90	Z111697
072	20MAR91	1991.215	4827	7,010 d, g	61.10	Z111697
073	22MAY91	1991.387	4890	7,010 d	61.28	Z111697
074	27JUL91	1991.568	4956	7,010 d, tp	61.48	Z111697
075	11OCT91	1991.776	5032	7,010 d, f, h	60.70	C56
076	17FEB92	1992.129	5161	7,010 d, e	60.28	C56
077	10JUN92	1992.441	5275	7,010 d, f	60.72	C56
078	12JUN92	1992.447	5277	9,145 d, tp	60.72	np[2]
079	22SEP92	1992.729	5379	7,010 a	60.30	C56
080	10JAN93	1993.030	5489	7,010 a	59.28	C56
081	16MAR93	1993.208	5554	7,010 a, tp	59.47	C56
082	10JUL93	1993.525	5670	7,010 a, tp	59.64	C56
083	10SEP93	1993.695	5732	7,010 a	59.10	C56
084	15NOV93	1993.876	5798	7,010 a	58.83	C56
085	14FEB94	1994.125	5889	7,010 d	58.27	C56
086	25FEB94	1994.155	5900	7,010 d	58.33	C56
087	16MAY94	1994.374	5980	7,010 d, tp	58.30	C56
088	13AUG94	1994.618	6069	7,010 a, tp	58.21	C56
089	07SEP94	1994.686	6094	7,010 a, tp	58.07	C56
090	31OCT94	1994.834	6148	7,010 a, tp	57.97	C56
091	25JAN95	1995.070	6234	7,010 d	57.53	C56
092	01MAY95	1995.332	6330	7,010 a, tp	57.55	C56
093	27SEP95	1995.740	6479	7,010 a	57.43	C56
094	03DEC95	1995.924	6546	7,010 a	57.06	C56

Table 1. Columbia Glacier vertical photography flights—Continued

Flight number	Date	t Decimal year[1]	D day number[1]	Flight altitude(m), coverage, and quality[2]		Glacier length (km)[3]	Camera file[4]
095	17FEB96	1996.132	6622	7,010	a	57.20	C56
096	29MAY96	1996.410	6724	7,010	d, h	57.31	C62
097	02JUL96	1996.504	6758	7,010	d, o	57.33	C63
098	02SEP96	1996.674	6820	7,010	d, o	57.17	C63
099	25OCT96	1996.819	6873	7,010	d, o	56.85	C63
100	10MAR97	1997.193	7009.61	2,600, 4,700, 7,010	d	56.90	C56
101	30MAR97	1997.248	7029.62	2,600, 4,700, 7,010	d	56.94	C56
102	09APR97	1997.275	7039.6	2,600, 4,700, 7,,010	d	56.97	C56
103	19APR97	1997.303	7049.6	2,600, 4,700, 7,010	d, o	57.01	C56
104	03MAY97	1997.341	7063.6	2,600, 4,700, 7,010	d	57.01	C56
105	21MAY97	1997.390	7081.65	2,600, 4,700, 7,010	d	56.92	C56
106	20AUG97	1997.638	7172	1,830	t	56.60	C56
107	12SEP97	1997.701	7195	3,050, 4,880	d	56.35	C56
108	15SEP97	1997.709	7198	7,410	d, f	56.35	C66
109	21APR98	1998.306	7416	3,050, 4,880, 7,010	d	56.30	C56
110	27MAY98	1998.407	7452	4,800	t, g	56.25	np[2]
111	12AUG98	1998.615	7528	3,050, 4,880, 7,010	d, h	56.20	C67
112	02OCT98	1998.755	7579	3,050, 4,880, 7,010	d, h	55.95	C67
113	22DEC98	1998.976	7660	3,050, 4,880, 7,101	d, h	55.28	C70
114	04MAR99	1999.174	7732	4,880	d, h, tp	55.60	C70
115	21MAR99	1999.220	7749	7,010	d, h, tp	55.60	C70
116	26SEP99	1999.738	7938	3,950, 7,620	d, f, h	55.15	C71
117	23OCT99	1999.812	7965	3,950, 7,620	d, f, h	54.65	C71
118	18SEP00	2000.716	8296	3,950, 7,620	d, f, h, tp	54.78	C70
119	20OCT00	2000.803	8328	3,950, 7,620	d, f, h, tp	54.50	C72

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[1]

solar year, or the time between two successive vernal equinoxes. The value of t shown for each flight refers to noon local civil time on the indicated date.

Where D = 1 on 1 JAN 78, and increases by 1 for each day thereafter, then $t = 1977.99863 + 0.00273791D$ gives the value of t at noon local civil time on the date corresponding to D. The cumulative effect of the annual variation of the length of the day from local true solar noon to local true solar noon) never exceeds 0.00003 solar year (Flamarrion, 1880).

[2] a = most of glacier;
b = whole glacier;
c = lowest 4 km;
d = lower reach;
e = icefall reach;
f = central basin;
g = very poor quality;
h = color;
o = oblique included;
t = terminus only;
np = no photogrammetry on this flight;
tp = terminus poorly defined.

[3] The glacier length (flights 1-62) is measured along a curvilinear centerline of the main branch as shown on figure 1 of Meier and others (1985). The terminus position is width averaged using a curvilinear Xi-Zeta grid as drawn by Meier (unpublished) during the early part of the USGS Columbia Glacier project. For flights 63-79 the length is width averaged between UTM x=496500 and UTM x=499000. Length after flight 79 was subjectively measured relative to the previous flight, referenced to the L points. Error in the glacier length is estimated to be 0.04 km.

[4] The camera files are give in the file CAMFILES on the CD-ROM in the pocket at the end of the report.

Table 2. An example of positions along the Columbia Glacier ice-water interface from the terminus file, in UTM eastings and northings, a portion of the file for 13AUG94
[UTM, Universal Transverse Mercator]

UTM (meters)		UTM (meters)		UTM (meters)		UTM (meters)		UTM (meters)	
Easting (X)	Northing (Y)	Easting (X)	Northing (Y)	Easting (X)	Northing (Y)	Easting (X)	Northing (Y)	Easting (X)	Northing (Y)
495426	6766471	495211	6768443	495497	6770221	497002	6771709	498731	6770652
495418	6766519	495193	6768494	495541	6770255	497047	6771736	498751	6770605
495410	6766569	495183	6768545	495562	6770302	497095	6771740	498772	6770553
495396	6766619	495169	6768599	495541	6770345	497144	6771755	498794	6770498
495389	6766670	495180	6768648	495528	6770401	497156	6771803	498811	6770450
495394	6766719	495197	6768698	495522	6770458	497128	6771847	498812	6770399
495404	6766767	495216	6768742	495524	6770513	497131	6771896	498853	6770301
495398	6766814	495232	6768787	495533	6770563	497180	6771913	498856	6770245
495396	6766866	495200	6768830	495534	6770615	497229	6771923	498891	6770206
495395	6766915	495180	6768876	495529	6770664	497279	6771911	498905	6770156
495405	6766966	495166	6768923	495553	6770720	497336	6771897	498911	6770106
495397	6767013	495146	6768971	495578	6770776	497388	6771900	498925	6770058
495378	6767060	495132	6769023	495613	6770823	497432	6771876	498946	6770012
495399	6767110	495128	6769071	495652	6770857	497471	6771848	498961	6769964
495393	6767161	495098	6769115	495691	6770889	497527	6771842	499007	6769942
495368	6767208	495062	6769149	495740	6770893	497575	6771861	499048	6769899
495346	6767253	495029	6769194	495782	6770844	497620	6771828	499088	6769855
495339	6767303	495000	6769243	495831	6770817	497665	6771791	499121	6769819
495344	6767354	494967	6769284	495881	6770788	497715	6771769	499158	6769780
495351	6767407	494931	6769320	495937	6770775	497764	6771751	499190	6769740
495374	6767448	494939	6769369	495981	6770798	497809	6771732	499218	6769692
495408	6767483	494957	6769418	496019	6770847	497852	6771708	499238	6769636
495441	6767526	494967	6769469	496047	6770900	497903	6771686	499259	6769584
495476	6767561	494966	6769519	496072	6770942	497954	6771669	499278	6769535
495520	6767588	494978	6769566	496112	6770979	498000	6771651	499299	6769491
495536	6767639	494984	6769614	496166	6770987	498043	6771613	499335	6769452
495519	6767684	494962	6769658	496201	6771021	498065	6771555	499376	6769414
495504	6767731	494936	6769702	496249	6771054	498092	6771498	499415	6769377
495490	6767777	494929	6769750	496301	6771085	498123	6771443	499451	6769342
495477	6767829	494924	6769799	496341	6771117	498153	6771396	499475	6769293
495463	6767879	494912	6769847	496378	6771151	498183	6771354	499482	6769244
495432	6767921	494951	6769875	496417	6771188	498216	6771310	499449	6769199
495426	6767969	494970	6769918	496450	6771225	498248	6771271	499434	6769154
495418	6768017	495005	6769956	496476	6771265	498279	6771235	499439	6769102
495372	6768005	495055	6769951	496501	6771311	498313	6771193	499420	6769058
495325	6767983	495103	6769945	496524	6771357	498340	6771153	499390	6769010
495277	6767985	495140	6769978	496569	6771387	498366	6771112	499365	6768966
495237	6768014	495184	6770003	496614	6771408	498415	6771092	499369	6768904
495272	6768047	495229	6770029	496662	6771439	498455	6771053	499384	6768853
495295	6768091	495264	6770067	496698	6771473	498487	6771017	499443	6768864
495310	6768137	495253	6770017	496735	6771523	498520	6770968	499493	6768870
495347	6768172	495296	6769986	496768	6771562	498543	6770908	499542	6768840
495340	6768230	495348	6770011	496807	6771593	498564	6770857	499589	6768820
495307	6768265	495362	6770058	496858	6771613	498591	6770810	499636	6768794
495277	6768309	495377	6770106	496913	6771616	498627	6770777	499655	6768743
495256	6768357	495417	6770146	496963	6771621	498673	6770757	499667	6768692
495232	6768400	495452	6770196	496998	6771662	498707	6770708	499669	6768684

Table 3. Columbia Glacier profile point locations from L46 to L57, and local transverse profiles at the L points
[UTM, Universal Transverse Mercator; B, transverse position on the profile]

		UTM (meters)	
L	B	Easting (X)	Northing (Y)
46	01	500619.88	6780573.0
46	02	500569.19	6780659.0
46	03	500518.47	6780745.5
46	04	500467.78	6780831.5
46	05	500417.06	6780918.0
46	06	500366.38	6781004.0
46	07	500315.69	6781090.0
46	08	500264.97	6781176.5
46	09	500214.28	6781262.5
46	10	500163.56	6781349.0
47	01	499766.66	6780055.5
47	02	499716.09	6780142.0
47	03	499665.53	6780228.0
47	04	499614.97	6780314.5
47	05	499564.41	6780400.5
47	06	499513.84	6780487.0
47	07	499463.28	6780573.5
47	08	499412.72	6780659.5
47	09	499362.16	6780746.0
47	10	499311.59	6780832.0
48	01	498948.53	6779529.0
48	02	498892.47	6779612.0
48	03	498836.41	6779694.5
48	04	498780.38	6779777.5
48	05	498724.31	6779860.0
48	06	498668.25	6779943.0
48	07	498612.19	6780026.0
48	08	498556.13	6780108.5
48	09	498500.09	6780191.5
48	10	498444.03	6780274.0
49	01	498217.78	6778947.0
49	02	498151.81	6779022.5
49	03	498085.84	6779097.5
49	04	498019.91	6779172.5
49	05	497953.94	6779248.0
49	06	497887.97	6779323.0
49	07	497822.00	6779398.0
49	08	497756.03	6779473.5
49	09	497690.09	6779548.5
49	10	497624.13	6779623.5
50	01	497566.59	6778278.0
50	02	497490.88	6778343.0
50	03	497415.16	6778408.5
50	04	497339.41	6778474.0
50	05	497263.69	6778539.0
50	06	497187.97	6778604.5
50	07	497112.25	6778670.0
50	08	497036.53	6778735.0
50	09	496960.78	6778800.5
50	10	496885.06	6778866.0
51	01	496968.84	6777527.0
51	02	496888.53	6777586.5
51	03	496808.25	6777646.0
51	04	496727.94	6777706.0
51	05	496647.66	6777765.5
51	06	496567.34	6777825.0
51	07	496487.03	6777884.5
51	08	496406.75	6777944.0
51	09	496326.44	6778004.0
51	10	496246.16	6778063.5
52	01	496519.41	6776778.5
52	02	496427.22	6776817.0
52	03	496335.03	6776856.0
52	04	496242.81	6776894.5
52	05	496150.63	6776933.5
52	06	496058.44	6776972.0
52	07	495966.25	6777010.5
52	08	495874.06	6777049.5
52	09	495781.84	6777088.0
52	10	495689.66	6777127.0
53	01	496379.78	6776016.5
53	02	496279.94	6776011.0
53	03	496180.06	6776006.0
53	04	496080.22	6776000.5
53	05	495980.34	6775995.5
53	06	495880.50	6775990.0
53	07	495780.66	6775984.5
53	08	495680.78	6775979.5
53	09	495580.94	6775974.0
53	10	495481.06	6775969.0
54	01	496543.22	6775082.5
54	02	496444.28	6775068.0
54	03	496345.34	6775053.5
54	04	496246.41	6775039.0
54	05	496147.47	6775024.5
54	06	496048.53	6775010.0
54	07	495949.59	6774995.5
54	08	495850.66	6774981.0
54	09	495751.72	6774966.5
54	10	495652.78	6774952.0
55	01	496526.88	6773943.5
55	02	496427.78	6773956.5
55	03	496328.66	6773970.0
55	04	496229.56	6773983.5
55	05	496130.44	6773996.5
55	06	496031.34	6774010.0
55	07	495932.25	6774023.5
55	08	495833.13	6774036.5
55	09	495734.03	6774050.0
55	10	495634.91	6774063.5
56	01	496410.34	6773000.0
56	02	496310.41	6773003.5
56	03	496210.50	6773007.5
56	04	496110.56	6773011.5
56	05	496010.66	6773015.5
56	06	495910.72	6773019.5
56	07	495810.78	6773023.5
56	08	495710.88	6773027.5
56	09	495610.94	6773031.5
56	10	495511.03	6773035.5
57	01	496524.47	6772160.0
57	02	496428.00	6772134.0
57	03	496331.53	6772107.5
57	04	496235.06	6772081.0
57	05	496138.59	6772055.0
57	06	496042.13	6772028.5
57	07	495945.66	6772002.0
57	08	495849.19	6771976.0
57	09	495752.72	6771949.5
57	10	495656.25	6771923.0

Table 4. A sampling of Columbia Glacier surface altitude points from file KMALT

[UTM, Universal Transverse Mercator; The UTM's of the points are significant to 1 meter; the altitude (Z) at the X, Y is accurate to 2–4 meters]

	UTM (meters)		
Flight number	Easting (X)	Northing (Y)	Z (meters)
70	496988.025	6768149.763	51.988
70	497083.560	6768178.623	52.486
70	497179.615	6768206.832	50.989
70	497278.601	6768239.085	55.981
70	497371.212	6768270.947	51.984
70	497467.598	6768299.210	61.470
70	497563.885	6768330.456	69.460
70	497658.409	6768360.476	69.959
70	497756.728	6768393.412	70.458
70	497842.861	6768427.135	69.460
70	496684.393	6769111.601	64.465
70	496780.224	6769138.365	65.964
70	496877.220	6769163.787	72.456
70	496969.703	6769191.473	76.449
70	497064.983	6769220.477	77.946
70	497171.295	6769248.592	89.428
70	497259.976	6769274.660	91.923
70	497357.756	6769305.022	92.421
70	497452.919	6769331.364	98.913

Table 5. A sampling of Columbia Glacier surface displacement between two dates (13AUG94 and 07SEP94)
[UTM, Universal Transverse Mercator]

Flight 88 (13AUG94)				Flight 89 (07SEPT94)			
	UTM (meters)				UTM (meters)		
ID	Easting (X)	Northing (Y)	Z (meters)	ID	Easting (X)	Northing (Y)	Z (meters)
80	495744.384	6772640.266	120.444	80	495879.652	6772193.148	88.694
81	495633.477	6773049.993	132.127	81	495663.039	6772620.066	101.941
82	496125.488	6772956.019	130.666	82	496206.030	6772532.313	89.638
83	496286.238	6773333.968	160.841	83	496287.070	6772960.505	82.539
84	496794.273	6773575.592	172.525	84	496786.084	6773309.165	100.993
85	497264.560	6773540.156	180.798	85	497269.102	6773446.607	161.092
86	497614.155	6773354.547	139.424	86	497615.769	6773333.489	129.857
87	497497.617	6773976.405	165.708	87	497505.019	6773965.126	150.678
88	496719.131	6773876.510	179.336	88	496687.898	6773598.246	178.596
89	496311.882	6773806.672	191.993	89	496243.398	6773470.655	171.498
90	495787.301	6773580.364	173.981	90	495716.928	6773230.422	142.630
91	495172.305	6773369.512	128.715	91	495119.986	6773063.308	127.484
92	494722.119	6773099.482	121.411	92	494714.064	6772913.899	108.080
93	494254.148	6773001.185	94.152	93	494260.647	6772985.225	91.986
94	493634.989	6772260.863	134.550	94	493641.260	6772257.463	119.432
95	493073.473	6772628.117	174.949	95	493073.043	6772622.130	161.075
96	492487.326	6772879.309	207.561	96	492487.039	6772872.841	208.399
97	491883.138	6773196.737	161.321	97	491875.742	6773192.645	143.089
98	491497.667	6773524.772	123.842	98	491498.736	6773519.560	130.783
99	494473.200	6773686.843	112.645	99	494465.095	6773671.428	100.024
100	494881.511	6773881.198	110.700	100	494809.884	6773707.764	97.657
101	495349.805	6773923.707	154.506	101	495257.537	6773650.709	141.195
102	495935.333	6774200.746	194.418	102	495864.940	6773876.472	186.149
103	496380.848	6774428.555	223.136	103	496352.690	6774100.181	187.094
104	496685.691	6774664.488	193.931	104	496714.898	6774411.595	189.459
105	497171.001	6774781.934	179.816	105	497199.397	6774688.759	167.217
106	497619.174	6774510.013	160.831	106	497618.664	6774501.973	161.534
107	496717.208	6774949.843	193.441	107	496765.664	6774699.612	175.728
108	496293.126	6774928.030	216.805	108	496318.413	6774593.824	187.558
109	495868.917	6774785.593	220.699	109	495864.058	6774469.179	181.876
110	495499.662	6774546.083	186.626	110	495460.349	6774266.959	167.678

Table 6. A sampling of Columbia Glacier speed

[Derived speed from point locations on 13AUG94 and 07SEP94, a 25-day interval. Directions in degrees, counter clockwise from south; ID, identification; UTM, Universal Transverse Mercator]

ID	Vector center UTM (meters) Easting (X)	Northing (Y)	Average Z (meters)	X difference (meters)	Y difference (meters)	Z difference (meters)	Distance (meters)	Speed (meters per day)	Direction (degrees)
80	495812	6772417	105	-135	448	32	468	18.7	-16.8
81	495648	6772835	117	-30	430	30	431	17.2	-3.9
82	496166	6772744	110	-81	424	41	431	17.2	-10.8
83	496287	6773147	122	-1	374	78	374	14.9	-.1
84	496790	6773442	137	8	267	72	267	10.7	1.8
85	497267	6773493	171	-5	94	20	94	3.7	-2.8
86	497615	6773344	135	-2	21	10	21	.8	-4.4
87	497501	6773971	158	-7	12	15	14	.5	-32.8
88	496704	6773737	179	31	279	1	280	11.2	6.4
89	496278	6773639	182	68	336	20	343	13.7	11.5
90	495752	6773406	158	70	350	31	357	14.3	11.4
91	495146	6773217	128	52	306	1	310	12.4	9.7
92	494718	6773007	115	8	186	13	186	7.4	2.5
93	494257	6772993	93	-7	16	2	17	.7	-22.1
94	493638	6772259	127	-6	4	15	7	.3	-60.8
95	493073	6772625	168	0	6	14	6	.2	4.2
96	492487	6772876	208	0	7	-1	7	.3	2.5
97	491879	6773195	152	7	4	18	8	.3	61.5
98	491498	6773522	127	-1	6	-7	6	.2	-11.2
99	494469	6773679	106	8	16	13	17	.7	27.6
100	494846	6773795	104	72	173	13	187	7.5	22.5
101	495304	6773787	148	92	273	13	288	11.5	18.7
102	495900	6774039	190	70	324	8	332	13.3	12.3
103	496367	6774264	205	28	329	36	330	13.2	4.9
104	496700	6774538	192	-29	253	4	255	10.2	-6.6
105	497185	6774736	174	-28	93	13	97	3.9	-17.0
106	497619	6774506	161	1	8	-1	8	.3	3.8
107	496741	6774825	185	-48	251	18	255	10.2	-10.9
108	496306	6774761	202	-25	334	29	335	13.4	-4.3
109	495867	6774627	201	5	317	39	317	12.7	.9
110	495480	6774407	177	39	279	19	282	11.3	8.0

Table 7. A sampling of Columbia Glacier "ice-to-be-calved" (File 088C)

[Ice was calved between 13AUG94 and 07SEP94, and the area of this ice can be delimited as a polygonal shape that is the top of the terminal ice cliff on the first date and a superposition of the ice very near the terminal ice cliff on the second date on the first date. UTM, Universal Transverse Mercator]

UTM (meters)		Z	UTM (meters)		Z	UTM (meters)		Z
Easting (X)	Northing (Y)	(meters)	Easting (X)	Northing (Y)	(meters)	Easting (X)	Northing (Y)	(meters)
495125.472	6769878.677	19.269	496013.569	6771689.564	83.463	497790.699	6771950.299	9.662
495112.332	6769924.986	19.268	496032.770	6771735.897	83.465	497821.236	6771905.343	28.873
495139.468	6769967.608	19.268	496042.483	6771780.940	85.483	497848.710	6771855.942	44.037
495163.290	6770010.358	21.291	496064.880	6771825.545	85.484	497876.817	6771814.926	44.037
495178.613	6770057.370	21.291	496085.635	6771870.494	85.484	497894.148	6771770.098	44.037
495194.703	6770102.615	19.775	496112.059	6771914.213	86.495	497911.569	6771724.604	44.543
495225.060	6770139.465	14.720	496135.701	6771963.336	86.495	497924.754	6771678.568	46.059
495254.021	6770182.306	13.203	496156.615	6772012.368	86.495	497880.355	6771700.544	23.816
495285.112	6770217.842	36.456	496185.172	6772055.457	86.495	497832.061	6771699.961	26.850
495306.652	6770261.717	36.455	496209.975	6772101.049	86.495	497790.713	6771727.997	27.356
495324.460	6770306.124	36.455	496226.973	6772159.703	67.287	497754.329	6771758.194	27.357
495353.017	6770349.815	41.004	496244.967	6772203.659	67.287	497710.105	6771781.745	23.313
495379.781	6770388.706	41.004	496270.353	6772242.254	74.365	497666.193	6771805.333	15.731
495384.307	6770440.420	33.421	496308.752	6772272.718	76.388	497619.514	6771824.728	14.720
495389.405	6770488.360	33.420	496350.340	6772298.256	76.893	497572.641	6771847.705	14.720
495391.366	6770536.408	32.410	496396.025	6772320.700	76.893	497523.658	6771855.483	13.709
495389.379	6770585.056	32.410	496443.334	6772328.225	76.893	497474.624	6771865.872	13.709
495401.036	6770631.079	32.409	496492.527	6772335.502	76.894	497427.376	6771876.968	13.709
495409.269	6770677.702	33.926	496543.709	6772346.333	82.959	497383.011	6771896.329	13.710
495424.598	6770727.205	33.926	496591.700	6772366.186	82.959	497342.854	6771924.487	13.709
495437.327	6770778.192	33.926	496646.952	6772358.828	82.959	497294.228	6771919.931	23.821
495449.265	6770827.581	35.947	496696.087	6772367.582	82.959	497251.022	6771939.166	23.819
495460.374	6770876.902	35.947	496746.144	6772374.695	82.959	497199.266	6771936.465	24.325
495461.207	6770924.129	35.948	496794.227	6772365.867	84.983	497151.448	6771926.152	28.370
495459.087	6770972.677	38.475	496851.685	6772361.382	84.983	497103.474	6771929.225	28.370
495466.536	6771021.022	38.474	496898.402	6772356.579	84.982	497056.982	6771915.421	28.876
495460.552	6771069.528	38.474	496943.932	6772320.418	122.388	497009.817	6771903.371	29.380
495468.794	6771119.702	38.474	496987.077	6772296.781	122.388	497027.340	6771857.071	31.910
495465.846	6771166.900	38.474	497033.346	6772286.894	122.388	497075.431	6771853.613	32.921
495470.308	6771203.860	66.276	497070.232	6772244.591	144.630	497124.915	6771844.055	32.921
495482.549	6771254.451	66.277	497125.910	6772284.399	42.016	497172.593	6771837.165	37.977
495493.212	6771301.397	66.277	497172.704	6772266.778	42.015	497219.592	6771823.574	37.975
495505.209	6771346.875	66.277	497213.577	6772230.984	51.619	497192.291	6771783.675	36.967
495520.951	6771392.453	69.310	497258.612	6772210.659	51.619	497147.458	6771758.295	32.923
495558.779	6771427.217	69.309	497301.503	6772191.947	41.004	497110.198	6771728.670	32.922
495595.173	6771459.905	69.310	497346.263	6772175.611	29.882	497085.565	6771683.324	32.922
495637.277	6771486.227	73.858	497394.439	6772157.409	29.882	497043.816	6771658.239	18.771
495681.653	6771514.591	73.858	497439.230	6772139.635	30.389	496999.493	6771638.254	19.276
495722.022	6771544.861	73.860	497487.165	6772120.807	30.388	496952.683	6771618.796	19.781
495768.026	6771558.329	73.858	497531.092	6772099.852	30.388	496905.762	6771629.182	16.748
495815.139	6771565.531	76.387	497576.225	6772078.442	1.029	496857.881	6771614.156	17.759
495864.314	6771586.292	76.387	497624.782	6772066.039	1.524	496813.598	6771589.316	17.760
495908.383	6771606.005	76.386	497667.316	6772037.426	9.662	496768.152	6771572.098	20.287
495955.102	6771618.432	83.463	497712.984	6772009.875	9.662	496747.849	6771524.201	31.914
495997.271	6771642.897	83.464	497751.486	6771980.971	9.663	496708.825	6771491.583	28.881

Table 7. A sampling of Columbia Glacier “ice-to-be-calved”(File ‘088C’)—Continued

UTM (meters)		Z (meters)	UTM (meters)		Z (meters)	UTM (meters)		Z (meters)
Easting (X)	Northing (Y)		Easting (X)	Northing (Y)		Easting (X)	Northing (Y)	
496672.728	6771459.909	28.881	495986.743	6770809.947	48.092	495509.327	6770478.981	.579
496632.103	6771431.591	29.893	495938.627	6770809.538	49.103	495510.527	6770429.745	1.455
496585.885	6771404.991	29.892	495889.335	6770792.375	49.104	495523.926	6770387.254	1.554
496542.250	6771379.498	48.597	495844.876	6770774.730	37.477	495554.079	6770349.999	1.554
496502.383	6771334.561	49.102	495807.061	6770805.884	37.983	495575.114	6770303.005	1.553
496469.349	6771293.072	49.101	495804.675	6770854.895	37.982	495551.554	6770251.594	15.239
496452.882	6771246.656	54.156	495764.185	6770876.807	44.050	495523.339	6770209.492	15.239
496429.024	6771211.048	37.981	495717.387	6770889.859	44.049	495492.757	6770164.428	15.239
496380.187	6771179.832	52.640	495668.943	6770893.674	44.050	495455.486	6770131.888	15.238
496351.100	6771136.592	56.179	495613.625	6770898.373	45.062	495417.107	6770096.662	10.689
496321.655	6771094.572	56.179	495565.271	6770894.820	42.028	495376.474	6770057.212	10.688
496281.296	6771064.831	56.178	495541.461	6770851.530	42.029	495351.145	6770014.237	10.688
496242.506	6771023.667	68.310	495514.803	6770811.641	42.028	495314.030	6769972.885	17.260
496193.367	6771003.026	68.310	495500.027	6770765.924	42.028	495267.828	6769962.607	17.260
496150.596	6770981.420	45.058	495502.838	6770717.158	42.028	495220.423	6769952.858	17.260
496105.928	6770965.087	45.057	495496.901	6770665.730	48.095	495184.967	6769921.068	17.260
496085.365	6770921.043	45.058	495495.061	6770616.656	48.095	495138.712	6769902.678	17.260
496047.619	6770891.654	45.565	495509.207	6770567.918	48.095	495148.319	6769902.823	23.326
496022.304	6770846.228	45.565	495513.179	6770525.607	8.161	495125.472	6769878.677	19.269

Table 8. Terminus position files for Columbia Glacier

File name	Number of points	File name	Number of points	File name	Number of points	File name	Number of points
001T	36	031T	94	061T	85	092T	202
002T	17	032T	81	062T	79	093T	208
003T	103	033T	87	063T	74	094T	108
004T	14	034T	94	064T	74	095T	283
005T	109	035T	79	065T	68	096T	296
006T	117	036T	73	066T	76	097T	122
007T	115	037T	72	067T	86	098T	120
008T	108	038T	70	068T	82	099T	134
009T	79	039T	75	069T	188	100T	234
010T	19	040T	72	070T	183	101T	227
011T	105	041T	73	071T	205	102T	248
012T	100	042T	73	072T	91	103T	270
013T	100	043T	76	073T	79	104T	206
014T	84	044T	72	074T	104	105T	148
015T	92	045T	61	075T	259	106T	383
016T	90	046T	75	076T	425	107T	296
017T	98	047T	79	077T	122	108T	200
018T	140	048T	73	079T	117	109T	846
019T	95	049T	77	080T	428	111T	171
020T	81	050T	68	081T	254	112T	566
021T	79	051T	60	082T	244	113T	345
022T	80	052T	65	083T	139	114T	201
023T	80	053T	63	084T	261	115T	156
024T	76	054T	59	085T	131	116T	219
025T	76	055T	59	086T	260	117T	132
026T	76	056T	69	087T	294	118T	180
027T	81	057T	69	088T	236	11 9T	185
028T	86	058T	66	089T	279		
029T	77	059T	72	090T	223		
030T	80	060T	75	091T	324		

Table 9. Altitude files for Columbia Glacier

File name	Number of points
037P	1,297
038P	1,302
039P	1,222
040P	1,221
041P	1,312
042P	1,273
043P	1,320
044P	1,293
045P	1,319
046P	1,325
047P	1,241
048P	1,246
049P	1,327
050P	1,319
055P	1,316
056P	1,283
057P	1,298
058P	1,291
059P	1,281
060P	1,301
061P	1,243
062P	1,285
063P	1,197
064P	1,204
065P	1,176
066P	1,138
067P	1,052
068P	1,038
069P	973
070P	1,200
071P	848
074P	1,088
075P	981
KMALT	5,780

Table 10. Displacement files for Columbia Glacier

[The single letter name extension ‘A’ indicates that additional flights (with different coverage) were flown on the same day.]

File name	Number of points	File name	Number of points	File name	Number of points	File name	Number of points
G001	266	043V-044	84	068V-069	6	090V-091	26
G002	223	044V-043	84	069V-068	6	091V-090	26
G003	137	044V-045	90	069V-070	18	091V-092	15
G004	221	045V-044	90	070V-069	18	092V-091	15
G005	73	045V-046	87	070V-071	60	092V-093	19
G006	68	046V-045	87	071V-070	60	093V-092	19
G007	64	046V-047	92	071V-072	7	093V-094	67
G008	162	047V-046	92	072V-071	7	094V-093	67
G009	196	047V-048	93	072V-073	5	094V-095	49
G010	222	048V-047	93	073V-072	5	095V-094	48
G011	227	048V-049	82	073V-074	40	095V-096	16
G012	202	049V-048	82	074V-073	40	096V-095	16
G013	202	049V-050	166	074V-075	41	096V-097	72
G014	193	050V-049	166	075V-074	41	097V-096	72
G015	272	050V-051	402	075V-076	25	097V-098	36
G016	247	051V-050	403	076V-075	25	098V-097	36
G017	193	051V-052	403	076V-077	27	098V-099	54
G018	193	052V-051	391	077V-076	27	099V-098	54
G019	169	052V-053	391	077V-079	30	099V-100	24
G020	175	053V-052	358	079V-077	30	100V-099	24
G021	151	053V-054	358	079V-080	11	100V-101	204
G022	162	054V-053	444	079V-080.A	19	101V-100	208
G023	146	054V-055	444	080V-079	11	101V-102	226
G024	149	055V-054	449	080V-079.A	20	102V-101	226
G025	134	055V-056	81	080V-081	69	102V-103	532
G026	129	056V-055	81	080V-081.A	29	103V-102	532
G027	127	056V-057	245	081V-080	69	103V-104	123
G028	125	057V-056	245	081V-080.A	29	104V-103	123
G029	123	057V-058	113	081V-082	18	106V-107	30
G030	123	058V-057	113	081V-082.A	31	107V-106	30
G031	216	058V-059	79	082V-081	18	108V-109	13
G032	211	059V-058	79	082V-081.A	28	109V-108	13
G033	205	059V-060	76	082V-083	25	111V-112	151
G034	196	060V-059	76	082V-083.A	35	112V-111	151
G035	198	060V-061	102	083V-082	25	112V-113	47
G036	193	061V-060	102	083V-082.A	34	113V-112	47
036V-037	87	061V-062	24	083V-084	31	113V-115	15
037V-036	87	062V-061	24	084V-083	31	114V-115	60
037V-038	86	062V-063	54	084V-085	11	115V-113	15
038V-037	86	063V-062	54	085V-084	11	115V-114	60
038V-039	95	063V-064	87	085V-086	98	115V-116	10
039V-038	95	064V-063	87	086V-085	99	116V-115	10
039V-040	84	064V-065	87	086V-087	22	116V-117	64
040V-039	84	065V-064	87	087V-086	22	116V-117.A	145
040V-041	95	065V-066	45	087V-088	24	117V-116	64
041V-040	95	066V-065	45	088V-087	26	117V-116.A	145
041V-042	93	066V-067	29	088V-089	171	118V-119	172
042V-041	93	067V-066	29	089V-088	171	119V-118	17
042V-043	111	067V-068	14	089V-090	39		
043V-042	111	068V-067	14	090V-089	39		

Table 11. Speed files for Columbia Glacier

[The single letter name extension "A" indicates that additional flights (with different coverage) were flown on the same day.]

File name	Number of points
V075-076	25
V076-077	27
V077-079	30
V079-080	11
V079-080.A	19
V080-081	69
V080-081.A	29
V081-082	18
V081-082.A	28
V082-083	25
V082-083.A	34
V083-084	31
V084-085	11
V085-086	98
V086-087	22
V087-088	24
V088-089	171
V089-090	39
V090-091	26
V091-092	15
V092-093	19
V093-094	67
V094-095	48
V095-096	16
V097-098	36
V098-099	54
V099-100	24
V100-101	204
V101-102	226
V102-103	532
V103-104	123
V106-107	30
V108-109	13
V111-112	151
V112-113	47
V113-115	15
V114-115	60
V115-116	10
V116-117	64
V116-117.A	145
V116-118	7

Table 12. “Ice-to-be-calved” files for Columbia Glacier

File name	Number of points	File name	Number of points	File name	Number of points
014C	70	039C	110	063C	100
015C	85	040C	117	064C	101
016C	88	041C	112	065C	121
018C	150	042C	136	066C	157
019C	104	043C	136	067C	103
020C	95	044C	117	069C	115
021C	96	045C	90	070C	136
022C	102	046C	81	073C	90
023C	86	047C	115	074C	112
024C	117	048C	129	075C	348
025C	105	049C	115	076C	121
026C	78	050C	128	077C	124
027C	91	051C	85	080C	236
028C	93	052C	87	081C	262
029C	118	053C	100	082C	111
030C	96	054C	107	083C	128
031C	122	055C	116	085C	77
032C	99	056C	129	088C	191
033C	98	057C	85	100C	218
034C	146	058C	88	101C	225
035C	128	059C	126	102C	216
036C	124	060C	126	103C	231
037C	105	061C	139	104C	211
038C	67	062C	123		