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Retrospective simulation of lake-level rise in Lake Bonney based on recent 21-yr record: indication of recent climate change in the McMurdo Dry Valleys, Antarctica

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Abstract

The physical and chemical characteristics of Lake Bonney, a permanently ice-covered closed basin lake in Taylor Valley, Antarctica are influenced significantly by local climate. The rising lake-levels of the past thirty years indicate a recent change in the local climate. We explored the significance of twentieth century changes in lake-level as a climate-change indicator by using a hydrologic model for the basin and a Monte Carlo simulation based on the variability in the available 30 yrs of hydrologic record. We compared the lake-level in the retrospective simulations with a measurement surveyed by Robert Scott's party in 1903. All the retrospective simulations based on the observed inflows yielded estimates that the lake was dry in 1903. It was necessary to remove 6 yrs from the observed 21-yr record for the retrospective simulation to match the measured 1903 lake-level for 50% of the simulations. From these analyses, we conclude that the period from 1969 to the present has had greater availability of solar radiation for meltwater generation, possibly brought about by changing cloud-cover patterns and coupled with a gradual warming trend. A third simulation indicated that an annual increase in inflow of about 3% between 1903 and 1973 would be required to match the 1903 measurement.

Introduction

One of the most extreme deserts of the world, the McMurdo Dry Valleys region of South Victoria Land, Antarctica, hosts a remarkable ecosystem and an unusual hydrologic system. High, rugged mountains flank the three main valleys – the Taylor, Wright, and Victoria Valleys – and alpine glaciers extend to the valley floors. The extreme aridity of the region causes sublimation to exceed precipitation at lower elevations, which is one cause of the ice-free nature of the McMurdo Dry Valleys (Fountain et al., 1998). The high Transantarctic Mountains also hinder ice intrusion into the Dry Valleys by effectively blocking the advance of the polar ice cap toward the Ross Sea.

Because the lakes do not have outflows to the Ross Sea, the difference between the inflow from glacial meltwater streams and the sublimation loss from the frozen surface is balanced by a volume change in the lake and a subsequent rise or fall of lake-level (Clow et al., 1988; Chinn, 1993). When meltwater generation exceeds ablation, the lake-level rises. As the lake fills, the surface area increases, and a larger surface area corresponds to a larger loss to ablation from the surface. Conversely, when ablation exceeds meltwater inflow, the lake-level falls. The New Zealand Antarctic Program began monitoring the level of Lake Vanda during the 1968–69 season and those of other lakes in the 1972–73 season. Since lake-level monitoring commenced, a substantial rise has been observed in the levels of all of the closed-basin dry valley lakes. The observed lake-level rise is driven by changes in local climate, and the possibility that lake-level fluctuations can be used as an indicator of the coupling between local climate and global climate change has been suggested (Wilson, 1967, Chinn, 1993).

Inflows into the closed-basin Lake Bonney are balanced by ablation from the surface of the lake. The ablation rate varies throughout the year depending on solar radiation, temperature, and wind. At latitude 78 °S, solar radiation is relatively intense during the austral summer, while ablation during the winter is controlled by wind (Clow et al., 1988). The strong katabatic winds of the winter months result in high (~ 1 mm d^{-1}) ablation rates from the lake surface. Most of the ablation occurs in the summer, however, because the ablation rate depends strongly on the gradient of vapor pressures, and the saturation vapor pressure is a strong function of the air temperature. High ablation rates do not necessarily coincide with melting events, and furthermore, annual ablation is controlled by seasonal rise in temperature rather than peak daily temperatures (Clow et al., 1988).

In addition to the influence of temperature, meltwater generation strongly depends on solar radiation. Meltwater originates at the surface of the glaciers as well as on the 20–30 m high glacier faces. The observed 2–5 fold diel variations in streamflow demonstrate the dominance of incident solar radiation as a control of meltwater production (Conovitz et al., 1998). This suggests that a substantial portion of annual inflow is controlled by solar radiation during the summer months. There is a large interannual variability of the availability of solar radiation, and because the seasonal rise in temperature is thought to remain relatively constant, mean summer temperature may be a secondary control on interannual variability. For these reasons, annual lake-level changes seem to be controlled by changes in annual inflow rather than changes in ablation. Thus, the lake-level changes can be used as a sensitive local climate-change indicator.

Other indications of recent climate change in the lakes, which may have been driven by change in climate, come from analyses of sediment cores (Doran et al., 1994, Spaulding et al., 1997). The goal of this study was to use the available lake-level records and a hydrologic model of the lake to estimate the lake level throughout the 20^{th} century, and derive a conclusion about the behavior of the local climate throughout this time. We modeled the lake levels retrospectively using a Monte Carlo simulation.

Site description

Numerous permanently ice-covered lakes fed by glacial meltwater generated from surrounding alpine and piedmont glaciers exist within the Dry Valleys. Meltwater streams typically flow only 6–10 weeks per yr. No vascular plants exist in the Dry Valleys, but many streams do support extensive algal mats. The climate of Taylor Valley is that of an extreme cold desert. Annual precipitation is generally less than 10 cm, and occurs only in the form of snow. The average high temperature is 7 °C in the summer and the average low temperature drops to –45 °C in the winter (Keys, 1980).

There are two distinct climate regimes in the Dry Valleys. The maritime climate near the Ross Sea at Explorer's Cove governs the flows of Fryxell basin streams, whereas the inland climate is more prevalent in the Lake Bonney basin (Fountain et al., 1998). The maritime climate is characterized by cooler, wetter conditions. It is often cloudy due to moisture from openings in the pack ice of the Ross Sea. The inland climate is much drier and slightly warmer (Chinn, 1993).

A moraine and bedrock ridge divides Lake Bonney (77 ° 45′S, 162 ° 15′E) into two lobes, which are connected with a narrow strait of water (Figure 1). The western party of Robert F. Scott's Discovery Expedition measured the width of the channel in the year 1903 at the narrowest point (Scott, 1905). Using the lake bathymetry that is available today, the 1903 lake-level was derived from this measurement (Chinn, 1993). Since 1969 the New Zealand Antarctic Program (NZAP) has measured the level of Lake Bonney on a regular basis. Changes in lake-level over time are shown in Figure 2.

The Taylor Glacier abuts the west lobe of Lake Bonney. The advance or retreat of the Taylor Glacier could affect the level of Lake Bonney by displacement causing non climate-related trends in lake-level fluctuations. Supraglacial lakes exhibit strong lake-level responses to glacial advancement, but most lakes whose basins are penetrated by glaciers appear to change negligibly (Chinn, 1993). Lake Bonney falls into this category. Taylor Glacier, although wet-based in part, is thought to be frozen to the ground at the snout. Although the glacier is believed to be advancing, the rate of advancement is probably no more than 1 m per yr (K. Lewis, personal communication). The length of the glacier/lake boundary is about 700 m, and the depth is approximately 21 m (Chinn, 1993). The displacement is therefore 14700 m^3 per m of advancement. This corresponds to a lake-level rise of less than a half cm per yr, a negligible amount compared to the observed changes in lake level.

Lake Bonney has a permanent ice cover which is up to 5 m thick (Chinn, 1993). The only substantial loss

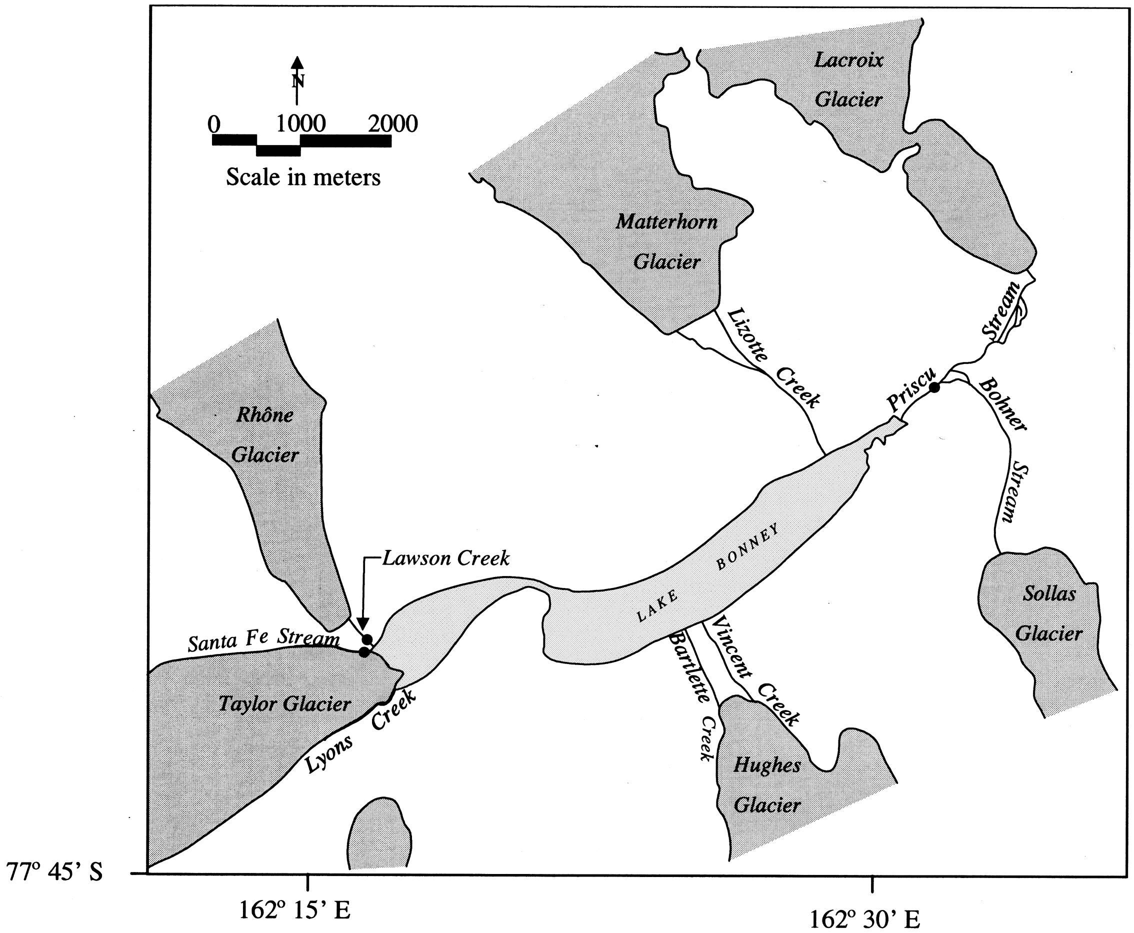

Figure 1. Lake Bonney basin.

of water from the lake is through sublimation of this ice cover. Some water loss through infiltration into the continental aquifer has been suggested by Chinn (1993), but it is thought not to be a significant amount relative to the sublimation loss from the surface.

Since the 1993–94 field season, the United States Antarctic Program (USAP) has gauged the streamflow into Lake Bonney at four sites (Figure 1). The sources of these streams are alpine glaciers which surround the basin. Some of the gauges use Parshall flumes, and others use natural controls (Von Guerard et al., 1994). All involve continuous stage monitoring using a nitrogen pressure transducer system. The stage data are collected at 15-min intervals, and are subsequently converted to flow data using established rating curves. All of the major streams – Priscu, Lawson, Lyons, and Santa Fe Streams – are gauged. Some lesser streams add inflow as well, which is estimated based on the flow in the gauged streams.

In addition to the streamflows measured in the Lake Bonney basin, we analyzed streamflows of the Onyx River, which is located in the Wright Valley. The Onyx River streamflow record is obtained through a USAP/NZAP collaborative program. Although it flows inland, the Onyx River has its primary sources at the Lower Wright Glacier, which is controlled by the maritime climate. The flow in the Onyx River reflects maritime climatic controls.

A summary of all hydrologic information data from 1903 to the present, including data to be modeled by the Monte Carlo simulation, is presented in Table 1. To prepare for a Monte Carlo simulation, an inflow record was generated with the available data. The available data include: (1) lake-level changes surveyed by the NZAP from 1972–73 through 1989–90 field seasons, (2) inflows into Lake Bonney commencing in the 1993–94 season, (3) a continuous record of Onyx River Flow in Wright Valley since 1969, and (4) bathymetry

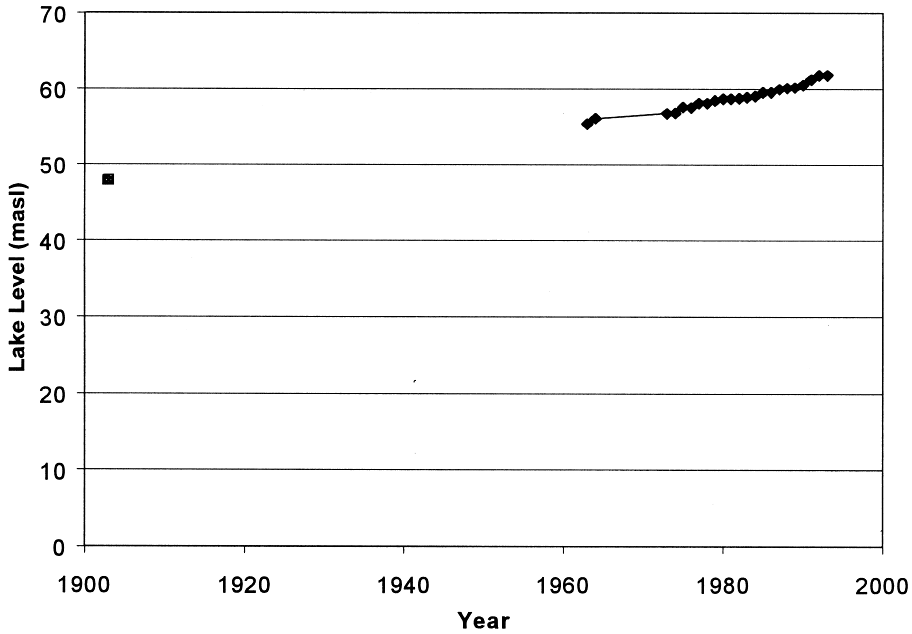

Figure 2. The rise of lake level of Lake Bonney.

polynomials generated by Schmok's November 1995 survey of the lakes (Schmok & Wellington, 1995).

Methods

Approach

From the Lake Bonney bathymetry, the average volume of water added annually to the lake between 1903 and 1973 is 3.8×10^5 m^3. The first level was taken in the 1972–73 season and the first volume change was calculated for the 1973–74 season. The average net annual added volume for 1973–74 through 1993–94 is 1.01×10^6 m^3, about 2.5 times higher than the net annual added volume for the period prior to 1973. This simple comparison does suggest that annual inflow has been greater in the most recent decades than earlier in this century, however, because this comparison neglects ablation from the ice cover, a more rigorous analysis is warranted. The volume of water lost to ablation, and therefore the net volume of water added (difference of volume inflow and volume of water lost to ablation), is a function of the surface area, which changed significantly throughout the century as the lake level rose. The area of the lake in 1903 was 2.59×10^6 m^2 according to the bathymetry polynomial. In 1973 the area was 3.65×10^6 m^2. This increase in area of 30% corresponds to an increase of 3.73×10^5 m^3 of annual ablation loss between 1973 and 1903. Thus, the increase in ablation loss is comparable to the average net added annual volume for 1903 to 1973, showing the importance of ablation in the hydrologic budget for dry valley lakes. The volume of water lost to ablation, as it varies with surface area from year to year, can be accounted for using a computer simulation, whereas a comparison of average inflows of the period 1903–1973 to inflows derived from measured level changes since 1973 neglects these differences and is therefore not an accurate indicator of climate response.

Table 1. Data and simulation summary

1903	Scott's party lake level meas.
1904–1972/73	Monte Carlo simulations (1, 2 and 3)
1972/73–1989/90	NZAP lake level measurements
1990/91–1991/92	Flow data from Onyx River correlation
1992/93	No data
1993/94–present	USAP measured flow

We did a retrospective Monte Carlo simulation of Lake Bonney level using recent inflows. Projecting back in time, a modeled lake level was compared with the 1903 lake level. We then used our simulation to quantify change in inflow responsible for the difference between modeled and observed lake levels. Ideally a

Monte Carlo simulation relies on many years of record, but in the case of Lake Bonney, only a limited 21-yr record is available. With such a low number of values, it is difficult to determine or define the distribution, although we found the available data to be useful in the Monte Carlo simulation.

To set up the model, we first generated an inflow record into Lake Bonney for the 21 yrs for which there are sufficient data to do so (1972–73 through 1993–94 seasons). For the years that the New Zealand scientists measured the lake-level, determining inflow was done simply by using the bathymetric polynomial (equation 1) to generate areas (Schmok & Wellington, 1995).

$$A = 4349485.384 - 146715.9816 \cdot Z + 1794.4519712978 \cdot Z^2 - 24.6405466957 \cdot Z^3 \quad (1)$$

where A = surface area of the lake (m^2); Z = depth of the lake relative to the November 1995 lake level. The net volumetric inflows (difference of inflow from the streams and ablation loss) into the lake can then be calculated using the formula for the volume of a truncated cone:

$$V = \left(\frac{h}{3}\right)\left(A1 + A2 + \sqrt{A1 \cdot A2}\right) \quad (2)$$

where V = net volumetric inflow to the lake; h = the level change from one year to the next; $A1$ = the present year's surface area; $A2$ = the previous year's surface area. The bathymetric polynomial for Lake Bonney (equation 1) is a function of depth relative to the level of the lake in November 1995. Although data exist with which to estimate inflows until 1993–94, lake level data is not available after 1989–90. The level of the lake in November 1995, on which surface area calculations are based, must be determined. This is done by estimating inflows into Lake Bonney to complete the post-1990 inflow record.

The net annual inflow determined by equation 2 is based on surface area of the lake and level change. The total stream inflow could be calculated as the sum of the net annual inflow and the ablation rate. The ablation rate was assumed to be uniform over the entire lake surface, and a larger surface area corresponds to a greater volumetric loss to sublimation. For this reason a volume change calculated when the lake has a larger surface area reflects a greater inflow from the streams than the same volume change calculated when the lake is at a lower level, because at a lower level the ablation loss would have been significantly less.

Calculation of 1990–91 and 1991–92 inflows into Lake Bonney

Gauging stations located on Lake Bonney tributaries were not operated during the 1990–91 and 1991–92 field seasons. Inflows during these years were estimated using a correlation with nearby gauges to fill in this gap in the record. The four years of annual discharge record for the eight streams flowing into Lake Bonney that are presently available were examined for possible correlations between years. Figure 3 shows a correlation between the 1993–94 and the 1994–95 records and includes the annual Onyx River flow. The Onyx River flow compared well with the trend for the Lake

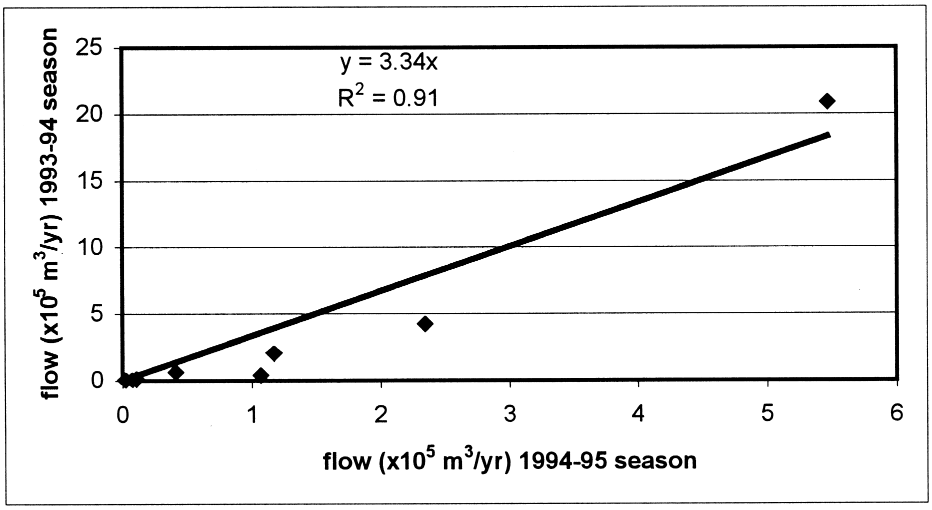

Figure 3. Correlation between 1993–94 and 1994–95 flows.

Bonney streams. Figure 4 shows a similar good correlation between 1994–95 and 1995–96 streamflows. This analysis indicates that the Onyx River flow can be used as a predictor for the flows of the Lake Bonney streams during the 2 yrs for which lake elevation and annual discharge records are not available. Although the Onyx River has its source in an area subject to the maritime climate, total annual flows correlate well with those from other years.

Because of the significant correlations, the ratio of Onyx River flow to 1994–95 Onyx River flow was applied to all of the Lake Bonney streams to generate a synthetic inflow record. Table 2 summarizes available flow record, and synthetic inflows generated using the Onyx River record are shaded. Inflows calculated using the lake elevation compiled by Chinn (1993) are net inflows and already account for losses due to ablation. The flows calculated by the correlations do not, however, and ablation must be estimated. Clow et al. (1988) found the average loss due to ablation to be 35 cm yr^{-1}. Using the surface area of Lake Bonney, an ablation loss was calculated, and the net inflows into Lake Bonney to be used in the Monte Carlo simulation were estimated. Lake elevation and streamflows were not observed during the 1992–93 field season. Not much is known about the behavior of the lake during that summer, and it is not known whether ablation exceeded inflow or vice versa.

Finally, to determine inflows in the span 1973–1990, using lake levels, the depth from the 1995 level must be known because the bathymetric polynomial is a function of the depth in 1995. It was therefore necessary to calculate the depth of Lake Bonney for each year for which the inflows had been calculated by correlation. This is an iterative process, and an initial guess was made at the level change. Volume inflows were based on these guesses, so the elevation changes were iterated until the inflows matched those calculated using the correlation. Because the 1990–91 elevation depends on the elevation in 1991–92, it is a complex relation, and several iterations were necessary to arrive at the solution. The depth for each year after 1973–74 was determined using Chinn's lake-level change data. This was then converted to annual net inflow to obtain the estimated 21-yr inflow record.

Distribution of the net annual inflow data

The flow series was matched with a statistical distribution so that the same flow probabilities could be modeled in the 70-yr period prior to 1973. Table 3 lists the generated inflows to be used in the Monte Carlo simulation. A histogram of the records is presented in Figure 5, showing the distribution of values since 1973. For example, there were three values in the inflow series since 1973 that fall between 3.5 and 8.5×10^5 m^3 yr^{-1}. By visual examination, the data evidently match neither a uniform distribution nor a normal distribution. The random variables are positively skewed, and so a lognormal distribution appears appropriate.

Lognormal distributions apply for strictly positive random variables ($X > 0$), and because for some years ablation exceeds inflow (negative net flow) the

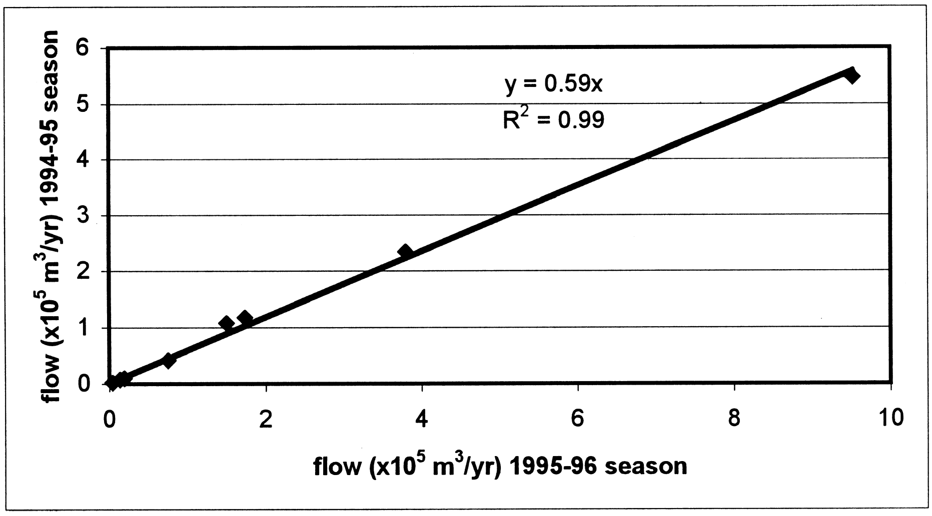

Figure 4. Correlation between 1994–95 and 1995–96 flows.

Table 2. Available flow data, including synthetic inflow data (m^3 yr^{-1}). Shaded data are inflows derived from correlations

Season inflow	Onyx	Priscu	Santa Fe	Lawson	Lyons	Red River	Lizotte	Bartlette	Vincent	Total
1996–97	762967	72826	188434	146312	544217	10884	4005	18206	13108	997992
1995–96	951800	75128	379413	149711	173560	3794	4132	18782	13523	818043
1994–95	546400	41200	234290	106680	117140	2340	2270	10300	7420	521640
1993–94	2087600	63531	421886	40975	203599	4106	1614	12601	6315	754627
1991–92	8345800	254124	1687544	163900	814396	16424	6456	50404	25260	3018508
1991–91	12020600	365938.56	2430063.36	236016	1172730.24	23650.56	9296.64	72581.76	36374.4	4346651.52

Table 3. Inflows used in the Monte Carlo simulation, generated by correlation and lake-level change data

Season	Bonney level (masl)	Delta h (m)	Depth (Z) (m)	Area (m^2)	Volume diff. (m^3)
1993–94	61.78	0.0235	0.000	4349485	102203.93
1991–92	61.76	0.5496	0.024	4346037	2366602.38
1990–91	61.21	0.7278	0.573	4265984	3066854.80
1989–90	60.482	0.334	1.301	4161598	1382067.57
1988–89	60.148	0.077	1.635	4114301	316383.33
1987–88	60.071	0.143	1.712	4103450	585355.75
1986–87	59.928	0.37	1.855	4083352	1501267.25
1985–86	59.558	0.06	2.225	4031661	241649.44
1984–85	59.498	0.482	2.285	4023321	1923173.92
1983–84	59.016	0.145	2.767	3956746	572286.06
1982–83	58.871	0.136	2.912	3936863	534148.91
1981–82	58.735	0.069	3.048	3918275	270036.32
1980–81	58.666	–0.023	3.117	3908867	–89939.98
1979–80	58.689	0.269	3.094	3912001	1047407.51
1978–79	58.42	0.325	3.363	3875444	1252383.73
1977–78	58.095	–0.011	3.688	3831568	–42155.4
1976–77	58.106	0.582	3.677	3833047	2208161
1975–76	57.524	–0.038	4.259	3755268	–142796
1974–75	57.562	0.794	4.221	3760316	2944072
1973–74	56.768	0.021	5.015	3655728	76741.5
1972–73	56.747	0.25	5.036	3652986	304415.5

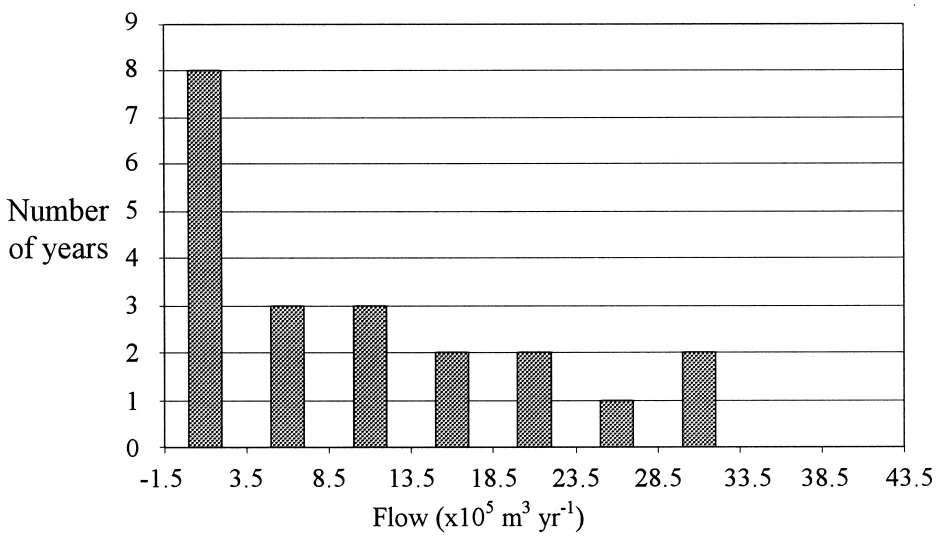

Figure 5. Histogram of 21-yr flow series, (× 10^5 m^3/yr).

following transform was performed for every inflow using $\xi = 145000$, chosen because it is the minimum value to the nearest thousand that ensures all positive $(X + \xi)$ values.

$$Y = \ln(X + \xi) \tag{3}$$

The random variables Y were plotted against the normal distribution (equation 4) in Figure 6.

$$f_y(y) = \frac{1}{\sigma_y\sqrt{2\pi}} \exp\left[-\frac{1}{2\,\sigma_y}\left(\frac{x-\mu_y}{\sigma_y}\right)^2\right] \tag{4}$$

Except for the outlier of the 1975–76 season, annual runoff volumes appeared to match the lognormal distribution very well, with $\xi = 145000$, $\mu_y = 13.27$, and $\sigma_y = 1$.

Frequency analysis

The flow series were ranked in descending order, and the exceedence probabilities of Y were calculated using the plotting position formula:

$$P = \frac{m}{n+1} \tag{5}$$

where P = exceedence probability of the event with rank m where $m = 1$ is the highest flow; n = the total number of inflows in the series. These exceedence probabilities were used to assign flows to each year of the simulation, based on the random number calculated for that year. It was necessary to determine a normally distributed random number in the interval (0,1), to compare with the series of Y values, from equation 3. This was done by first generating a uniform (0,1) random number (Etter, 1990) and converting it to a normal random number with $\mu = 0$ and $\sigma = 1$ using: (Odeh & Evans, 1974)

$$\in(u) = t + \frac{p_0 + p_1 t + p_2 t^2 + p_3 t^3 + p_4 t^4}{q_0 + q_1 t + q_2 t^2 + q_3 t^3 + q_4 t^4} \quad 0.5 \le u < 1 \tag{6a}$$

$$\in(u) = + \in(1-u) \quad 0 < u < 0.5 \tag{6b}$$

$$t = (-2\ln(1-u))^{½} \tag{6c}$$

where u is a uniform (0,1) random number, and

$p_0 = -0.322232431088$, $p_1 = -1$, $p_2 = -0.342242088547$, $p_3 = -0.0204231210245$, $p_4 = -0.0000453642210148$, $q_0 = 0.099348462606$, $q_1 = 0.588581570495$, $q_2 = 0.531103462366$, $q_3 = 0.103537752285$, $q_4 = 0.0038560700634$.

Equation 6 generates random numbers to approximate the probability density function (pdf) given by equation 4. This function has the form as shown in Figure 7. If a is a normally distributed random number as generated by equation 6, then the cumulative density function (CDF) given is shown as the shaded area. It is the area under the pdf up to the random number a.

The CDF (shaded area in Figure 7) can be expressed mathematically as:

$$F(x) = \int_{-\infty}^{a} f(x)dx \tag{7}$$

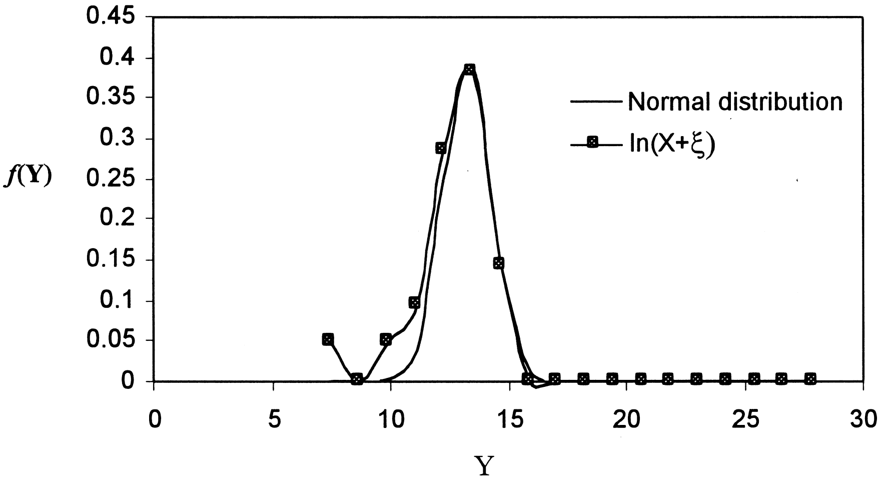

Figure 6. Comparison of logarithms of flow series with normal distribution.

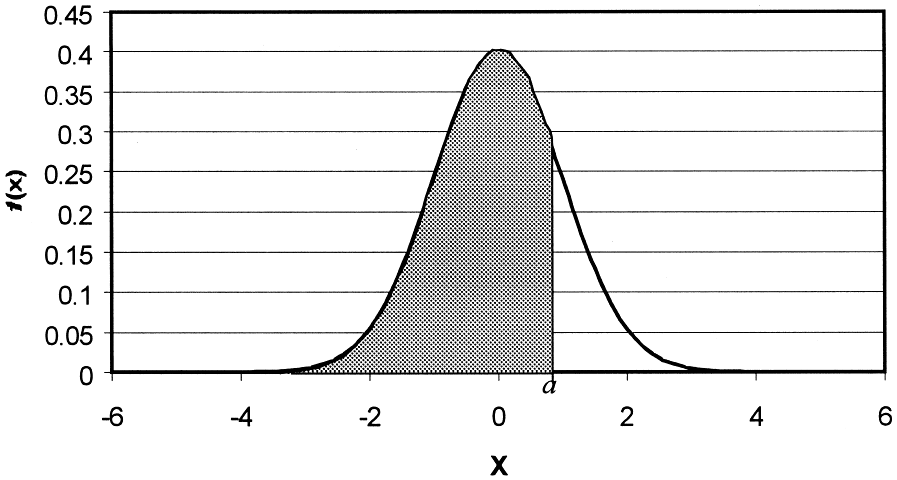

Figure 7. Diagram showing the probability density function, with the shaded area representing F(x).

The FORTRAN program *Monte Carlo* integrates $F(x)$ numerically, using a step size $dx = 0.01$. Equation 7 gives the probability that a number of less than or equal to a will be generated. Note that:

$$\int_{-\infty}^{\infty} f(x)dx = 1 \tag{8}$$

i.e. the total area under the curve of the pdf is 1. The result is that $F(x)$ as given by equation 7 is a normally distributed random number on the interval (0,1). The quantity $(1–F(x))$ can be seen as an exceedence probability, and it is this value that was compared with exceedence probabilities from the plotting positions P.

If a generated value of $F(x)$ falls between one value of P and a higher value of P, the flow corresponding to the higher level of P, as generated by equation 5, was used as the inflow for that year. This procedure for determining flow was repeated for all 70 yrs, to generate a synthetic flow record for the entire 70 yrs, based on the statistics derived from the 21-yr record that is available.

Determination of the area

The goal was to compare lake elevation computed for 1903 to actual lake-level in 1903. To do so, depth was determined as the simulation proceeded backwards in time toward the year 1903. This was done by solving iteratively for an area and depth of a previous year, given a net volume inflow for that year. This was done using a function call in *Monte Carlo*, which is of the form:

$$r(x) = [A(depth)] - A_{predicted} \tag{9}$$

$A(depth)$ is the area calculated by the predicted depth, from equation 1, and $A_{predicted}$ is the area that is guessed to begin the iteration. The function $r(x)$ has the graphical form as shown in Figure 8.

In Figure 8, A2 is a year's lake area for any given year, and A1 is the guessed area for the previous year at the first iteration. *Monte Carlo* uses a bisection algorithm to solve this function. In *Monte Carlo*, the area A1 for which $r(x) = 0$ is taken as the previous year's lake surface area. If A1 is not small enough, i.e. if r(A1) is negative, A1 is reduced by a factor of 0.9 until r(A1) becomes positive. This ensures that *Monte Carlo* can zero in on the true value of A1. If this loop

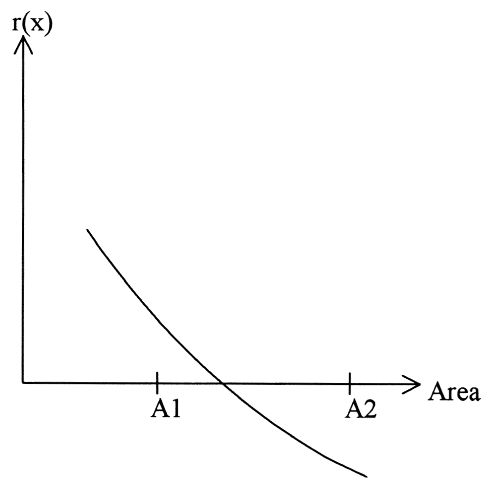

Figure 8. Graphical form of the residual function r(x).

becomes infinite, it means that A1 is negative, indicating that the modelled lake has gone dry.

Ablation loss influencing simulated meltwater inflow

The volumetric inflow assigned to years when the lake was substantially lower is based on the distribution corresponding to high lake stands, as calculated from observed lake-level changes. At low lake stands, the lake had a smaller surface area, and thus a smaller ablation loss. This lower ablation loss is not reflected in the use of a net inflow from the applied distribution, which was generated for the years 1973–1995. This implies that because the ablation loss was higher in recent years, the water flowing into the lake was even greater than in earlier years. This observation strengthens the argument that a shift in climate has occurred to allow for more energy available for meltwater production throughout the century.

Monte Carlo simulation

A schematic of the Monte Carlo model is depicted in Figure 9. *Monte Carlo 1* estimates lake-surface elevation throughout the century using the generated inflow series. Two variations of the Monte Carlo model were then developed. *Monte Carlo 2* determines the same probability that the lake-level as observed by Scott will be attained, but with a certain number of the highest flows removed from the inflow series. Thus a number is input by the user. *Monte Carlo 3* modelled 1,000 runs as well, and the basic shape of the distribution based on the 21-yr record was held constant. That is, the positively skewed lognormal distribution was still assumed valid, but each year's flow was manipulated by:

$$F_i = F_p \cdot C^i \qquad (10)$$

where F_i = flow in year i used in the simulation; F_p = flow value from inflow series; C = a factor representing the annual warming ($C < 1$). *Monte Carlo 3* determines the value of C necessary to reach the lake-level observed in 1903. Figures 10 and 11 show schematic diagrams of the fundamental differences of the manipulations of *Monte Carlo 2* and *Monte Carlo 3*. *Monte Carlo 2* assumes that extreme events have occurred in the 21 yrs for which flow and lake-level records exist, and the observed high lake-level results from these unlikely events. The underlying assumption is that equation 5 is not valid, because

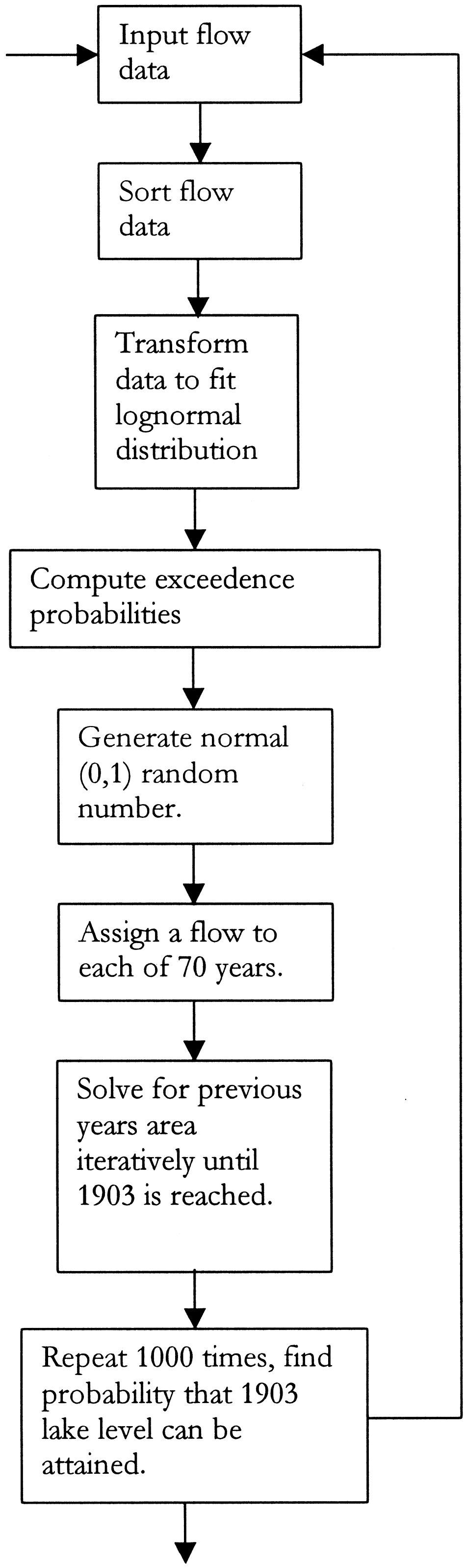

Figure 9. Schematic diagram of the *Monte Carlo* FORTRAN model.

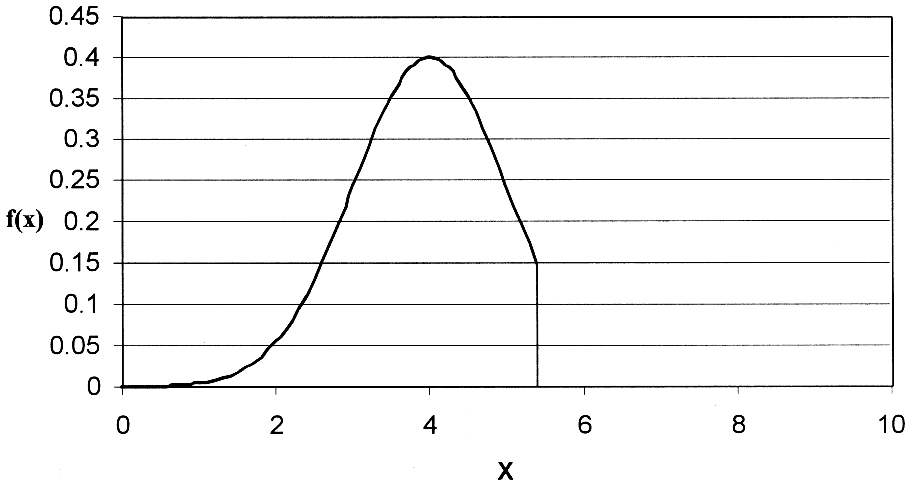

Figure 10. The manipulation of the inflow series showing the type of omission necessary to simulate the observed data point.

adequate information about the inflows is lacking. *Monte Carlo 3*, on the other hand, assumes that equation 5 is valid and the probabilities of exceedence of observed high-flow events (such as the 1990–91 season) are not extremely low.

Results

Monte Carlo 1 simulation

In the *Monte Carlo 1* simulation using the 21-yr record, one thousand different possible scenarios of the inflows of the past were simulated. The simulated lake elevations throughout the 70-yr period prior to 1973 are shown in Figure 12. Of the 1,000 simulations, not one predicted a level as high as the 1903 lake elevation of 47.85 m observed by the *Discovery* expedition's party. In fact, all of the scenarios predicted that Lake Bonney was dry in 1903. On average, inflows to Lake Bonney from 1903–1973 must have been significantly lower than the inflows since 1973. This result indicates that substantial changes have occurred in the climate in west Taylor Valley, as well as in the Dry Valleys.

Monte Carlo 2 simulation

Extreme events occur as a result of unusual meteorological conditions. In the case of very high flow years, they result from an exceptionally large number

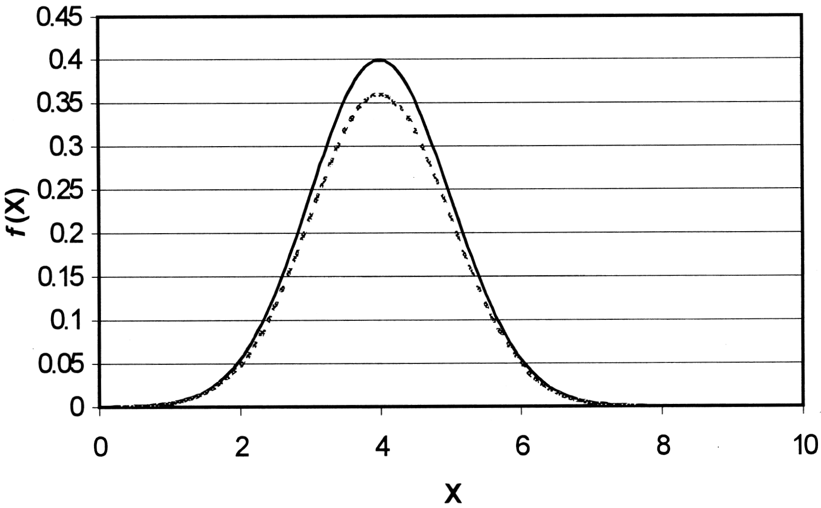

Figure 11. The manipulation of the inflow series assuming equations 3–5 apply.

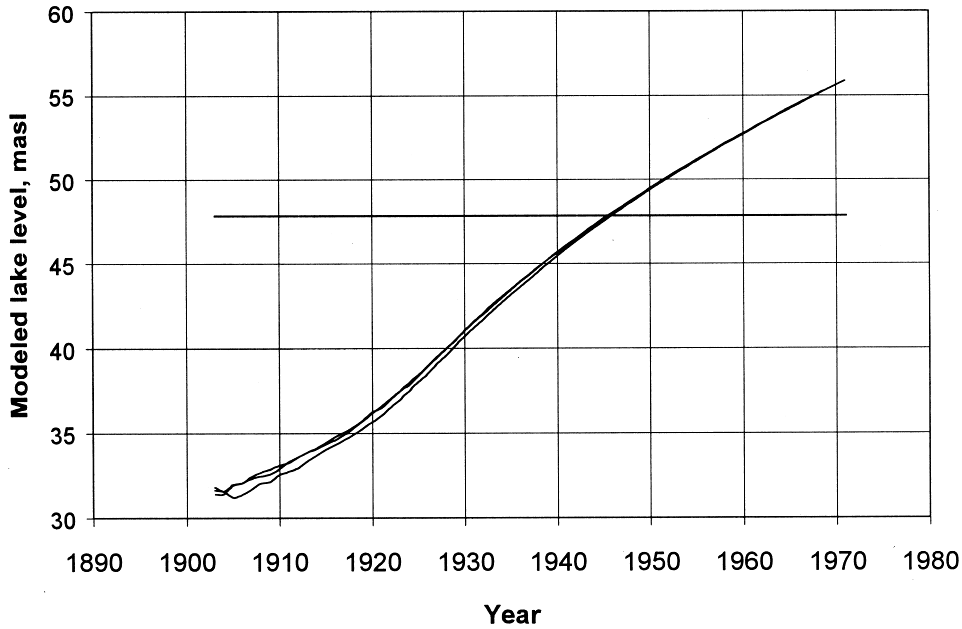

Figure 12. Three simulated lake-level scenarios. The horizontal line represents the level observed by the *Discovery* Expedition's western party.

of degree-days above the melting point of ice. They may not necessarily be well represented by the exceedence probabilities assigned to them by equation 5, because so few years of record exist. Because there are only 21 yrs record, the predicted exceedence probability for the highest inflow event is 1/(21 + 1) = 0.045. A very high flow, like that of the 1990–91 season, is likely to have a much smaller exceedence probability, but it can not be known exactly. We explore the possibility that the results of the *Monte Carlo 1* simulation were influenced by extreme events in the *Monte Carlo 2* simulation.

The goal of the *Monte Carlo 2* simulation was to determine how the inflow distribution must be manipulated in order to correctly predict the 47.85 m lake-level observed in 1903. This was done by omitting specified numbers of high flow events from the distribution and then rerunning the model. For each run with a different number of excluded high-flow values, the program calculated the percent chance (based on 1000 simulations) that the 1903 data point could be reached. Table 4 summarizes the results. The simulation is then run for the sum of seventy and the number of excluded points to obtain the results presented in Figure 13.

The simulation results show that the largest nine flow years must be omitted to achieve the observed 1903 lake-level with near 100% certainty. The largest 6 yrs, almost one third of the record, must be omitted to achieve the lake-level with 50% certainty. This result suggests that 6 out of the 21 inflow events are so extreme that their exceedence probabilities are negligible, and the probability that all six would occur within a 21-yr period is the product of six very small probabilities and is therefore so small that it can be effectively disregarded. Consequently, the data obtained in recent years certainly shows a trend toward a greater number of degree-days above 0 °C, or increased solar radiation resulting from a decrease of cloud cover.

In 1970–71 a tremendous inflow from the Onyx River caused Lake Vanda to rise 2058 mm (Chinn, 1993), some 650 mm more than the next-highest extreme inflow. The 1970–71 level change of Lake Vanda can not be compared to Lake Bonney, because it precedes lake-level monitoring at other lakes. It can

Table 4. Results of Monte Carlo 2 simulation

No. omitted	Percent chance
9	100
8	99.4
7	91.9
6	51.1
5	12.7
4	2.5
3	0
2	0
1	0

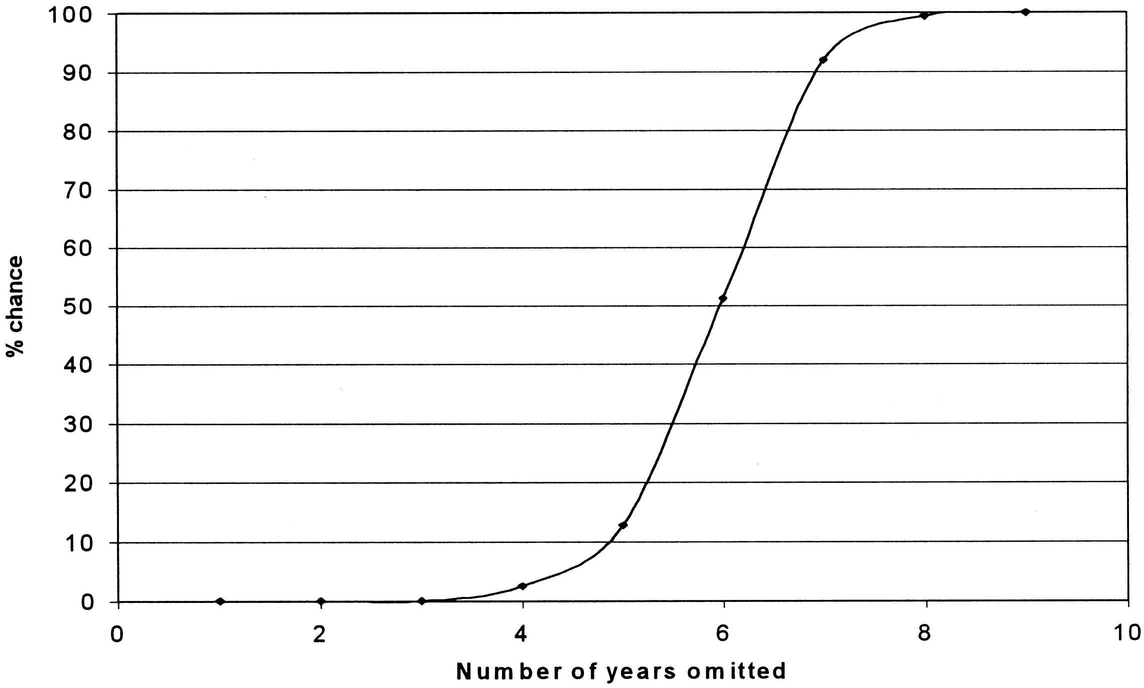

Figure 13. The percent chance that the 1903 data point is reached vs. the number of omitted high-flow events, as simulated by *Monte Carlo 2*.

be assumed, from the excellent correlation of Onyx Flow to Lake Bonney Basin flows, that a comparable event occurred in the Lake Bonney Basin, and that it far exceeds the high flow events used in the Monte Carlo simulations. This provides further credence to the idea that the local climate of the Lake Bonney basin had substantially more solar radiation in the last three decades.

Monte Carlo 3 simulation

Another possibility is that the high flow events do not qualify as extreme events, but occur naturally from time to time. In this case the lognormal distribution may have applied to the inflow series, but the magnitude of all of the flows has increased over time, on average. This scenario could also account for the much lower simulated lake level of Lake Bonney and would lead to a nonlinear trend of lake level over time.

Equation 10 suggests that on average, in any given year, the flow is 1/C times larger than in the previous year. The *Monte Carlo 3* model predicts a C value of 0.968, based on 1000 simulations. Various lake-level curves for different values of C are presented in Figure 14. The results of this simulation show that a continuing increase in meltwater flow into Lake Bonney throughout the twentieth century can explain the observed patterns. This result implies a greater availability of solar radiation for meltwater generation at the glacial source possibly combined with an increase in the number of degree-days above 0 °C.

Discussion

One of the few measurements taken by the first explorers of the McMurdo Dry Valleys that can be used to determine the status of the lakes at the time was the measurement of the width of the narrow strait connecting the two lobes of Lake Bonney. Chinn (1993) used this data point and bathymetric data to determine the level of the lake in 1903. In this study, we have developed a 21-yr inflow record for the lake (from 1973–1995) and used the variability in the record as a basis for retrospective Monte Carlo simulations of lake-level back to 1903. The single reference point from 1903 and the short duration of the recent inflow record are significant limitations for our analysis. Such limitations are an inherent aspect of addressing recent climate change in the dry valleys because of the long hiatus in scientific activity between the first exploration and the beginning of monitoring programs by the New

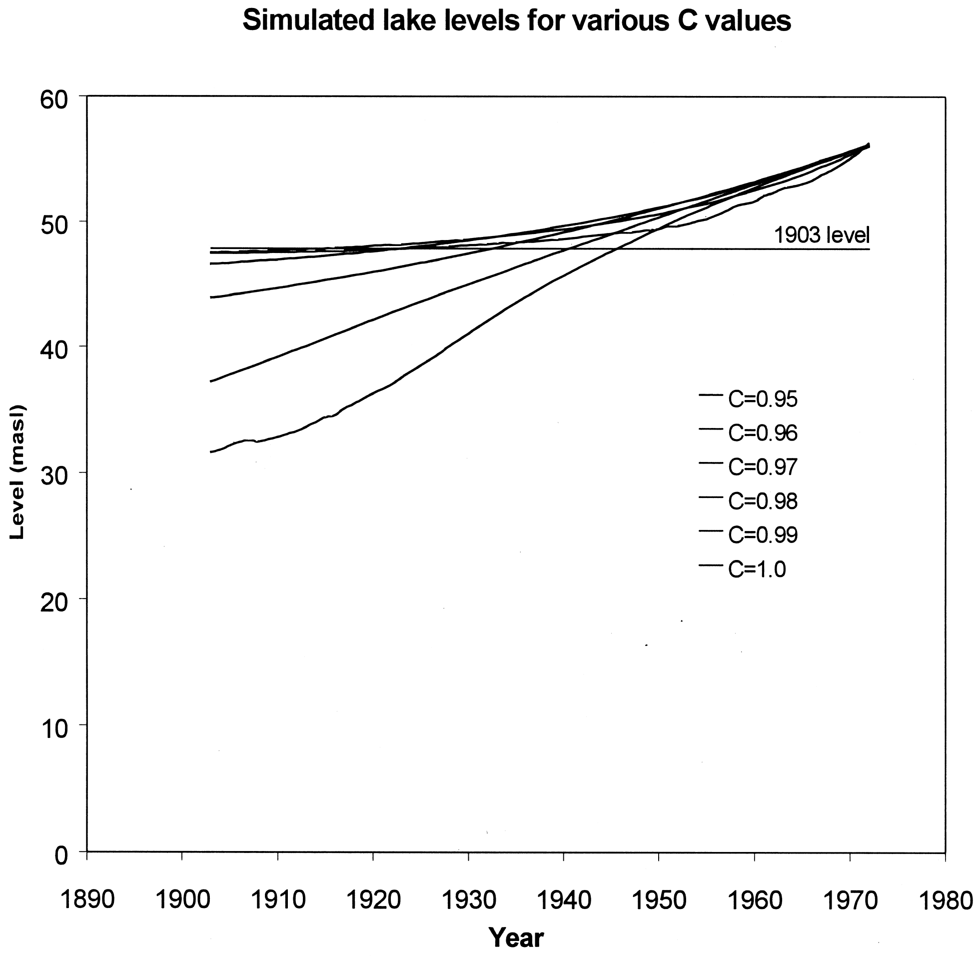

Figure 14. Results of *Monte Carlo 3* – Lake level behavior for various values of C.

Zealand Antarctic Program in 1969. A further consideration is that our approach underestimates net inflow in earlier years at lower lake-levels by not accounting for lesser ablation losses having occurred for the smaller lake surface areas of the past.

In our retrospective analysis using a series of three Monte Carlo simulations, the potential constraints for interpretation of the results associated with the limited data were overwhelmed by the magnitude of the change in climate indicated by the simulations. All 1000 simulations based upon the recent 21-yr record gave a result that the lake was dry in 1903. In the second simulation, it was necessary to remove 6 high flow years from the record to obtain the measured lake-level, which refutes an interpretation that inflow distribution in the 21-yr record was skewed by extreme events. In the third simulation, a rate of change in annual inflow with an increase of about 3% per yr was sufficient to match the 1903 lake-level. Although a gradual continuous increase in solar radiation and summer temperatures may have occurred, the rapid rise in Lake Vanda in the 1970–71 season, recorded prior to the measurements of Lake Bonney began, suggest that the climate change has been recent and abrupt, rather than gradual. The paleolimnological evidence from the sediment record for fossil diatoms in Lake Hoare (Spaulding et al., 1997) is consistent with these changes having occurred recently.

Comparison with other polar climate indicators

Worldwide, the Earth's surface temperature has risen by between 0.3 and 0.6 °C over the past century (Cane et al., 1997). Whether this trend is the result of anthropogenic forcing of the Earth's atmosphere through accumulation of greenhouse gases or reflects

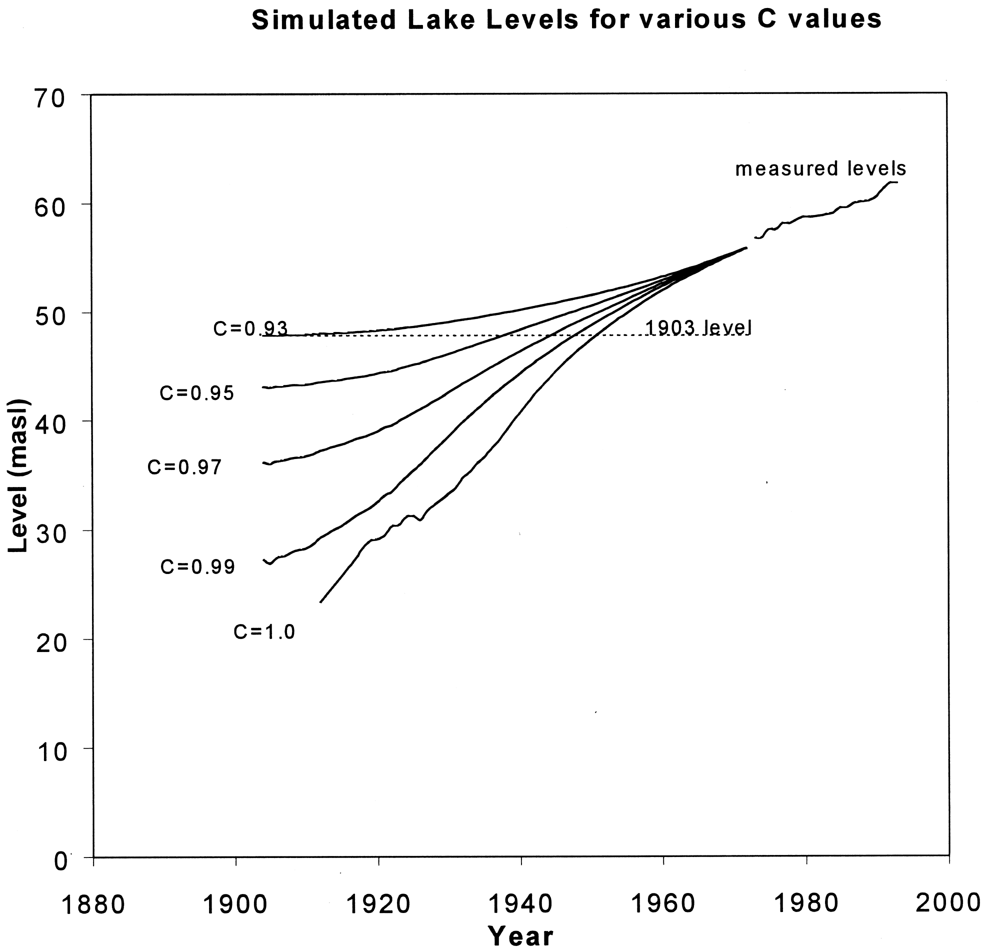

Figure 15. The simulated lake levels for various values of C, correcting for ablation changing with area.

the Earth's natural climate variability is not fully understood. Nonetheless, various studies of temperate freshwater systems have identified patterns of rapid change that suggest a climatic forcing rather than natural climate variability (Cook et al., 1991, Douglas et al., 1994; Cane et al., 1997). These abrupt changes would appear to resemble our results of recent rapid lake-level rise for Lake Bonney in the Dry Valleys.

In studies of climate change, proxy data for climate from polar regions are of particular interest because global circulation models typically indicate that climate changes may be amplified in the polar regions (Roots, 1989). The rapid change in the summer climate in Taylor Valley indicated by our retrospective simulations of lake-level is consistent with general trends exhibited by other proxy data from polar regions. Overpeck et al. (1997) compiled paleoclimate records based on tree ring, lake and marine sediment, and ice core records of the past 400 yrs in the Arctic and found a warming trend from 1840 to the mid-twentieth century. This trend is responsible for the retreat of Arctic glaciers and receding glacier equilibrium lines. Warming in polar regions is likely to be intensified by positive feedbacks, such as decreased albedo resulting from receding pack ice (Overpeck et al., 1997). Continued monitoring of lake-level, streamflow and meteorological conditions in the Dry Valleys will be useful in comparing changes in climate in both polar regions.

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