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Influence of volcanic dust on glacier mass balance at high latitudes

EXPLOSIVE eruptions, which inject large quantities of volcanic dust into the Earth's upper atmosphere, are believed to be important factors in climatic change. Theoretical considerations suggest that the greatest climatic effect of a stratospheric dust veil would be at high latitudes during summer months, when solar radiation passes through the greatest depth of atmosphere and the surface is illuminated continuously[1]. Furthermore, the residence time of volcanic dust is greatest at high latitudes, where it may remain in the upper atmosphere for a decade or more, depending on particle size and initial injection height[2]. Here we present evidence that the eruption of Mount Agung (8 °S, 115 °E) in March 1963, was responsible for a marked change in the climate of the North American High Arctic and that this change has had a significant impact on glacier mass balance in the region.

The North American High Arctic (north of lat. 74 °N) contains the greatest concentration of land-based snow and ice outside Greenland and Antarctica, with glaciation levels in some areas < 300 m above sea level[3]. The ablation, or melt, season averages 86–123 d yr^{-1} near sea level and up to 53% of annual precipitation may occur during this period[4]. At higher elevations, the ablation season is even shorter and all summer precipitation falls as snow, increasing surface albedo and continuously retarding the melt process at the glacier or ice cap surface. Because this season is so brief, a change in summer climate has significant impact on glacier mass balance in the region.

Table 1 Change in average annual melting degree day totals ($T_x + T_n$, °C).

Station	First complete annual record	Mean: start of record to 1963	Mean: 1964–76	%*
Thule	1947	937	604†	65
Eureka	1948	808	702	87
Resolute	1948	616	462	75
Alert	1951	505	440	87
Isachsen	1948	458	339	47

*Post-1963 average as a % of pre-1964 average.
†1964–74 inclusive.

An abrupt and significant change in the summer climate of the Canadian Arctic occurred between the summer of 1963 and 1964 and the resulting conditions have persisted[4,5]. Mean July freezing-level heights in the atmosphere in the decade after 1963 were up to 500 m lower than in the preceding decade. At the surface, mean maximum July temperatures since 1963 have averaged 1.1 °C to 2.7 °C lower than in the pre-1963 period. This fall in temperature was partly brought about by a change in the frequency of extremely warm summer days. At Alert, for example, there was an average of 2.3 d yr^{-1} with maxima > 15.5 °C (60 °F) between 1950 and 1963; between 1964 and 1976 there have only been four such days[4].

Particularly useful indices of the change in total summer 'warmth' are annual melting degree day totals over the past 25–30 yr. A melting degree day (MDD) is the difference between 0 °C and daily maximum (T_xMDD) or minimum (T_nMDD) temperatures, when the latter are above 0 °C. Melting degree day totals have fallen significantly throughout the High Arctic since 1963 (Table 1). This is most apparent at Thule, Greenland (Fig. 1), where mean MDD totals 1964–1974 were only 65% of the average from 1947 to 1963, with the greatest changes occurring in the months of June and July.

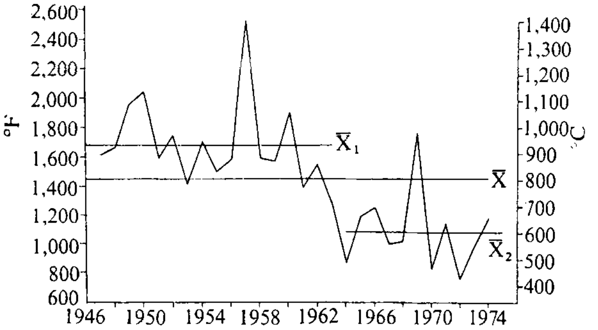

Fig. 1 Annual ($T_x + T_n$) MDD totals at Thule, northwestern Greenland, showing the abrupt decrease in overall 'summer warmth' after the eruption of Mount Agung in 1963.

How has this change in summer climate affected glacier mass balance in the region? It has been argued that mass balance measurements from the north-west sector of the Devon Ice Cap (taken since 1960 and comprising the longest series of such measurements in the Canadian Arctic) show no evidence of a cooling trend[6]. These data are highly correlated with T_nMDD indices at Resolute and Thule ($r = -0.94$, $y = -2.79x + 224.8$; $P < 0.001$) (Thule and Resolute are the two long-term weather stations closest to the Devon Ice Cap, ~400 km and ~350 km to its east and west, respectively). It is interesting that extrapolation of the relationship to a situation where the annual T_nMDD total is zero results in a mass balance of 225 kg m^{-2} a^{-1}, which is very close to present accumulation amounts on the summit of the ice cap (220 kg m^{-2} a^{-1}) (ref. 6).) Using this regression equation, mass balance on the north-west Devon Ice Cap can be reconstructed back to 1947–48, when instrumental observations were first kept at both Thule and Resolute (Fig. 2). By putting the recent mass balance measurements in perspective, the post-1963 change is seen to be highly significant. Between 1947 and 1963, the ice cap continuously lost mass, with greatest losses occurring in the late 1950s. In the last decade, positive balance years have outnumbered negative balance years, although overall there

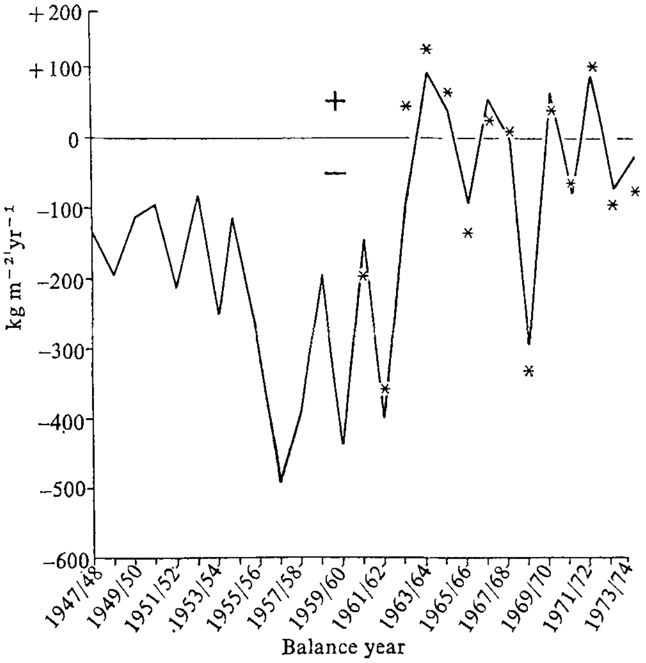

Fig. 2 Reconstruction of mass balance on the northwestern sector of the Devon Ice Cap, based on a regression equation between Devon mass balance since 1960 and average T_n MDD totals at Thule and Resolute. Stars indicate actual mass balance observations from Koerner[6], 1977.

has still been a net mass loss since 1963. This is seen clearly in Fig. 3, where cumulative mass losses since 1947 are shown. Between 1947–48 and 1963–64, we estimate the Devon Ice Cap lost ~3,500 kg m^{-2}, whereas since 1963–64 the net loss has been <350 kg m^{-2}. Similar studies using the only other long series of mass balance data in the High Arctic (from the White Glacier, Axel Heiberg Island)[7,8] show that these results are probably typical of an extensive area of the North American High Arctic and that the change in climate since 1963 has thus had an impact on snow and ice bodies of the region.

It is suggested that this change in summer climate is related to the massive input of volcanic dust into the upper atmosphere as a result of the eruption of Mount Agung in March 1963. The total dust veil in the Northern Hemisphere from 1963 to 1968 was the greatest since the period 1883–90, following the huge eruption of Krakatau (6 °S, 105 °E) in August 1883 (refs 1, 2). Dust veil index values in the mid-1960s were 1,100 compared to 1,500 after Krakatau[2]. Recent work[10,11] indicates that the greatest change in Northern Hemisphere surface temperatures in the past 25 years was related to the input of Mount Agung dust into the stratosphere. The dust affected solar radiation receipts at high latitudes of the USSR (71–81 °N) by late 1963 (ref. 14), and the effect is clearly seen in solar radiation and temperature data for Resolute (Fig. 4). In summer 1964, diffuse radiation reached the highest levels ever recorded and direct radiation fell to the lowest values on record. This increase in diffuse and decrease in direct radiation (often with no change in total radiation receipts) is a typical 'volcanic dust signal' and is very similar to that recorded at Aspendale, Australia in summer 1963, when direct radiation was reduced by 24% (by Agung dust in the stratosphere) but diffuse radiation almost doubled[13]. Unfortunately no solar radiation data are available for Resolute before 1961, so it is impossible to compare post-Agung values with any long-term pre-eruption value. However, there is some indication in Fig. 4 that summer diffuse radiation values decreased slowly from 1964 to 1969 (while direct radiation values increased). This may reflect stratospheric dust gradually settling out following the eruption. It is interesting that summer solar radiation receipts in 1972 were similar to 1964; diffuse radiation receipts were very high, and direct radiation very low. The summer of 1972 was the coldest since records began in 1947 (the only summer colder than 1964).

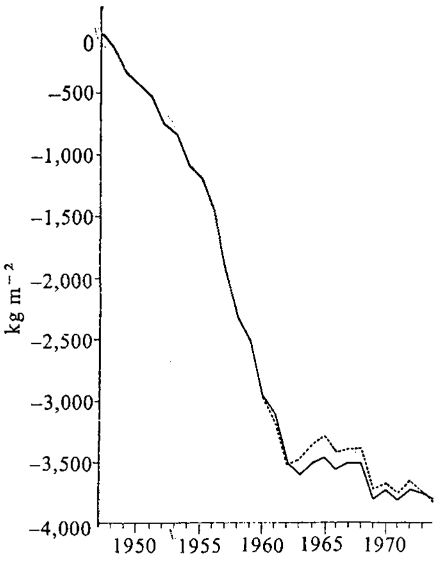

Fig. 3 Reconstruction of cumulative mass loss on the northwest Devon Ice Cap since 1947. The abrupt change in net loss since 1963 is clearly shown.

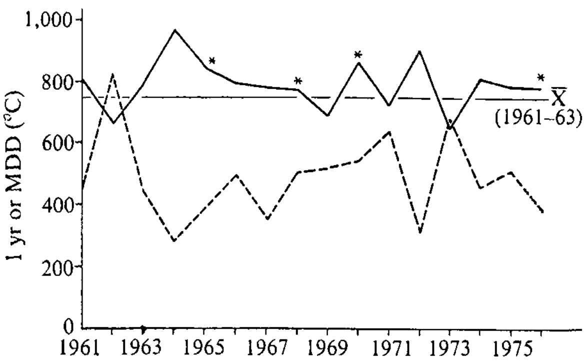

Fig. 4 Mean diffuse solar radiation receipts (June–August) at Resolute, NWT. The marked increase in diffuse radiation following the Agung eruption and the inverse relationship between diffuse radiation and (T_X+T_n) MDD at Resolute ($r = -0.83$) is shown. Solid line, June–August, diffuse radiation; dashed line (T_X+T_n) MDD. Stars indicate data for ≤ 1 month estimated.

Figure 4 also shows an inverse relationship between summer diffuse radiation and (T_x+T_n) MDD totals at Resolute. The correlation ($r = -0.83$) is statistically significant ($P<0.001$), indicates that diffuse radiation totals are closely linked to summer 'warmth', which in turn is a critical factor affecting glacier mass balance, as discussed above. Hence, in periods with large amounts of volcanic dust in the atmosphere, diffuse radiation totals would be high, surface MDD totals would be low and glacier mass balance would be positive.

If the Agung eruption was responsible for the change in ablation season conditions and mass balance during the 1960s, then it is likely that other periods of frequent volcanic activity resulted in temperature changes in the High Arctic at least as large as those observed since 1963. Thus it is probable that in the period 1750–1880 (when there were at least 14 eruptions of a magnitude equal to or greater than that of Agung) ablation season temperatures in the High Arctic were extremely low. Consequently, glacier mass balance was almost certainly positive during this interval, as indicated by stratigraphic studies of the Devon Ice Cap[6] and the Gilman glacier[14]. Conversely, the period 1920–63 (when volcanic activity was exceptionally low) was probably characterised by predominantly warm summers with more negative mass balance conditions[15]. Hence, the warmer period seen in Fig. 1 before 1964 was probably typical of summers back to the 1920s and the climate and mass balance conditions of the post-Agung period may be more typical of conditions characteristic of the last century.

RAYMOND S. BRADLEY
Department of Geology and Geography,
University of Massachusetts, Amherst 01003
JOHN ENGLAND
Department of Geography,
University of Alberta, Edmonton, Canada T6G 2H4

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