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Gletscher und globale Erwärmung

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Résumé de l'article

L'analyse des carottes de glace et les mesures du bilan de masse des glaciers, des calottes glaciaires et des indlandsis permettent de déceler des changements environnementaux survenus dans le passé tout en permettant de surveiller les changements actuels. Ces études peuvent contribuer au débat portant sur les conséquences physiques de l'activité humaine sur le climat. Trente-deux ans de données accumulées sur les bilans de masse, la fonte et l'accumulation de neige sur les glaciers de l'Arctique canadien ne montrent aucune tendance significative, bien que les bilans de masse soient quelque peu négatifs. Les modèles prévoient pourtant un réchauffement provoqué par l'apport accru d'aérosols d'origine industrielle. Nous observons une forte augmentation des concentrations de polluants industriels dans la neige déposée depuis les années cinquante, ce qui rend l'absence d'une tendance dans nos observations encore plus surprenante. L'absence d'indices sur un réchauffement dans l'archipel de la Reine-Élisabeth est peut-être simplement attribuable aux variations régionales du changement climatique, un phénomène qui devrait être étudié dans d'autres régions circumpolaires. Depuis 150 ans, une tendance vers un réchauffement à l'échelle planétaire a été observée à partir des données recueillies par les instruments ainsi que dans les carottes de glace. Les données obtenues à partir des carottes de glace et de la géométrie des glaciers semblent indiquer que ce réchauffement est plus marqué l'été que l'hiver. La tendance au réchauffement n'est cependant pas exceptionnelle dans le contexte des 10 000 ou 100 000 dernières années; elle pourrait rendre compte de la variabilité naturelle du climat.

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Essais

GLACIERS AND GLOBAL WARMING*

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ABSTRACT Ice core and mass balance studies from glaciers, ice caps and ice sheets constitute an ideal medium for monitoring and studying present and past environmental change and, as such, make a valuable contribution to the present debate over anthropogenic forcing of climate. Data derived from 32 years of measurements in the Canadian Arctic show no significant trends in glacier mass balance, ice melt, or snow accumulation, although the mass balance continues to be slightly negative. Models suggest that industrial aerosol loading of the atmosphere should add to the warming effect of greenhouse gases. However, we have found a sharp increase in the concentration of industrial pollutants in snow deposited since the early 1950's which makes the trendless nature of our various time series surprising. Spatial differences in the nature of climatic change may account for the lack of trend in the Queen Elizabeth Islands but encourages similar investigations to this study elsewhere in the circumpolar region. A global warming trend over the past 150 years has been demonstrated from instrumental data and is evident in our ice cores. However, the ice core data and glacier geometry changes in the Canadian Arctic suggest the Arctic warming is more pronounced in summer than winter. The same warming trend is not unique when viewed in the context of changes over the past 10,000 or 100,000 years. This suggests the 150-year trend is part of the natural climate variability.

RÉSUMÉ *Les glaciers et le réchauffement climatique.* L'analyse des carottes de glace et les mesures du bilan de masse des glaciers, des calottes glaciaires et des indlandsis permettent de déceler des changements environnementaux survenus dans le passé tout en permettant de surveiller les changements actuels. Ces études peuvent contribuer au débat portant sur les conséquences physiques de l'activité humaine sur le climat. Trente-deux ans de données accumulées sur les bilans de masse, la fonte et l'accumulation de neige sur les glaciers de l'Arctique canadien ne montrent aucune tendance significative, bien que les bilans de masse soient quelque peu négatifs. Les modèles prévoient pourtant un réchauffement provoqué par l'apport accru d'aérosols d'origine industrielle. Nous observons une forte augmentation des concentrations de polluants industriels dans la neige déposée depuis les années cinquante, ce qui rend l'absence d'une tendance dans nos observations encore plus surprenante. L'absence d'indices sur un réchauffement dans l'archipel de la Reine-Élisabeth est peut-être simplement attribuable aux variations régionales du changement climatique, un phénomène qui devrait être étudié dans d'autres régions circumpolaires. Depuis 150 ans, une tendance vers un réchauffement à l'échelle planétaire a été observée à partir des données recueillies par les instruments ainsi que dans les carottes de glace. Les données obtenues à partir des carottes de glace et de la géométrie des glaciers semblent indiquer que ce réchauffement est plus marqué l'été que l'hiver. La tendance au réchauffement n'est cependant pas exceptionnelle dans le contexte des 10 000 ou 100 000 dernières années; elle pourrait rendre compte de la variabilité naturelle du climat.

ZUSAMMENFASSUNG *Gletscher und globale Erwärmung.* Die Analyse von Eisbohrkernen und das Studium der Bilanz der Masse von Gletschern, Eiskappen und Eisdecken sind ein ausgezeichnetes Mittel, um gegenwärtige und vergangene Umweltveränderungen zu kontrollieren und zu studieren. So kann ein wertvoller Beitrag zur gegenwärtigen Debatte über den Einfluß der menschlichen Aktivität auf das Klima geleistet werden. Die Daten, die man durch Messungen über 32 Jahre in der kanadischen Arktis gewann, zeigen keine erhebliche Tendenz in der Bilanz der Gletschermasse, Eisschmelze oder Schneeakkumulation, auch wenn die Bilanz der Masse weiter leicht negativ ist. Die Modelle lassen vermuten, daß die Ladung der Atmosphäre mit Industrieaerosolen zum Treibhauseffekt beiträgt. Jedoch haben wir einen starken Anstieg in der Konzentration industrieller Schadstoffe in dem seit den frühen fünfziger Jahren angesammelten Schnee, was das Fehlen einer Tendenz in unseren verschiedenen Zeitabschnitten überraschend macht. Örtliche Unterschiede in der Natur der Klimawechsel mögen für das Fehlen einer Tendenz auf den Queen Elizabeth Inseln verantwortlich sein, doch dieser Untersuchung vergleichbare Studien sollten andernorts in der Region um den Pol durchgeführt werden. Eine globale Erwärmungstendenz über die vergangenen 150 Jahre konnte mittels instrumenteller Messungen festgestellt werden und ist in unseren Eisbohrkernen sichtbar. Indessen lassen die Eisbohrkerndaten und Veränderungen in der Geometrie der Gletscher in der kanadischen Arktis annehmen, daß die Erwärmung der Arktis im Sommer deutlicher ist als im Winter. Diese Erwärmungstendenz ist nicht außergewöhnlich, wenn man sie im Kontext der Veränderungen in den letzten 10,000 oder 100,000 Jahren sieht. Die 150 Jahre-Tendenz ist wohl Teil der natürlichen Klimavariabilität.

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INTRODUCTION

In the context of climatic change, glaciers, ice caps and ice sheets are of especial importance for: 1) monitoring present climate change; 2) investigating the mechanisms and patterns of past climatic change, and 3) quantifying past and present trends of atmospheric composition in both gaseous and aerosol form. This paper will consider these topics primarily by reference to the ice caps and glaciers of the Canadian high Arctic.

I. GLACIER RECORDS AND MONITORING CLIMATE

The relationship between glaciers and climate is usually considered by relating the climate either to changing glacier geometry (thickness, area and terminus position) or to changes of the glacier's mass balance.

GLACIER GEOMETRY

In non-stagnant glaciers the relationship between changing geometry and climate is extremely complex. The response time of glaciers to changing climate (Nye, 1960) varies between several thousands of years in the great ice sheets to less than a hundred years in small temperate glaciers. Changing geometry is usually in the form of terminus/edge recession (advance) in a warming (cooling) climate or thickening (thinning) in the central parts of the glacier/ice cap with increased (decreased) snow accumulation. The amount of change depends on the dynamic state of the glacier. Mountain glaciers with high accumulation/ablation rates respond dramatically to climatic changes. Glaciers in low snow accumulation areas, such as the Canadian Arctic show slow and limited response.

A limited study of aerial photography and Landsat imagery in the Queen Elizabeth Islands has shown that, with the exception of a few glaciers, there was only a modest change in the area of glaciers and ice caps in the Queen Elizabeth Islands between the 1940's and 1970's (Koerner, 1989). Three known cases of substantial change include a 6.5 km retreat of Sydkap Glacier on southern Ellesemere Island between 1957 and 1974, a 4-6 km advance of Otto Glacier between 1950 and 1964, and a 2 km advance of Good Friday Glacier on Axel Heiberg Island between 1952 and 1959. In addition, some very small ice caps disappeared during the 1950's (Koerner, 1989). Overall, the changes, set against a warming of approximately 1°C (from ice core records) over the past 100 years, confirm that high Arctic glaciers, in terms of area, are poor indicators of climatic change. A further limitation of relating area changes to climatic change is illustrated from work on Meighen Ice Cap. Measurements between 1960 and the present-day show that, while the ice cap edges have been retreating, the central parts have been thickening at a rate of 90-100 mm/yr. The balance is only slightly negative, not as negative as the marginal recession would suggest.

Measurements in boreholes on Devon (Paterson, 1976) and Agassiz Ice Caps (Fisher, 1993) have also not shown any significant changes of ice thickness over the past two decades. Repeated gravity measurements on Devon Ice Cap confirm the borehole measurements there. Levelling on Sverdrup Glacier (Devon Ice Cap) in 1965 and again in 1975 and 1986 also show no significant change in elevation at 300 m asl. Arnold (1968) using traditional surveying techniques, also found no elevation changes in the accumulation zone of Gilman Glacier (northern Ellesmere Island) between 1957 and 1967. However, Arnold (1981) did find significant lowering of the ice surface in the ablation zones of Gilman and White Glaciers in the 1950's and 60's. The unchanging accumulation zone elevations but slight ablation zone changes suggest unchanging accumulation rates but slightly increased melting over a large part of this century.

GLACIER MASS BALANCE

The net balance of a glacier is the difference between accumulation (c), which is usually in the form of snow, and ablation (*a*), which is usually in the form of melting of ice and snow which leaves the glacier as meltwater. The measurements are made each year at a number of representative points in both the accumulation (S_c) and ablation (S_a) areas of the glacier. The net mass balance (B_n) is then:

$$B_n = {}_{S_c}\!\int b_n dS + {}_{S_a}\!\int b_n dS \qquad \text{I}$$

Full details of the techniques can be found in Paterson (1981). Worldwide measurements of glacier balance can be found in the six volumes of 'Fluctuations of Glaciers' (IAHS, 1967, 1973, 1977, 1985, 1988, 1993) which cover the years from 1959 to 1990.

Mass balance measurements provide a much more accurate view of the health of a glacier and can be more easily related to climate than fluctuations in glacier shape. Many of the circumpolar records are now long enough for monitoring climate (Brugman and Koerner, 1991; Hagen *et al.*, 1991; Cogley *et al.*, 1995). A brief review of these records covering the past three decades, shows that while an overall negative balance still predominates, there is either no trend detectable in the data as is the case in the Queen Elizabeth Islands of Arctic Canada (Figs. 1 and 2), and Svalbard (Hagen *et al.*, 1990) or, as in northern Sweden, there is a recent slight increase in the number of positive balance years (Johnsson, 1991). The lack of a significant trend of increasingly negative balances runs counter to GCM predictions based on increasing levels of greenhouse gases but is substantiated by the study of Kahl *et al.* (1993) of temperatures in the lower troposphere over the Arctic Ocean , where no evidence was found for greenhouse warming between 1950 and 1990.

There is still, however, one drawback in using mass balance to detect climatic change. Firstly, mass balance is affected by changing glacier area. For example, consider a case where summers become warmer, but snow accumulation does not change. A glacier will initially respond by expanding its ablation zone into the accumulation zone. The glacier terminus will retreat and the ablation zone will become thinner. After a period of time determined by the

size of the glacier, the glacier will have reduced its ablation area to match the changed climate. However, during that process glacier balance will become less and less negative as the ablation zone decreases in area with no further change of climate. A simplistic, but incorrect conclusion, would be that the climate is cooling because the balance is becoming less negative.

To overcome the area problem the separate components of ablation and accumulation must be preserved as separate time series (Koerner, 1988). The records of poles lost due to reducing ablation area must be discarded (their inclusion will exaggerate the melt component in the early part of the record) and poles moving downslope must be replaced as close to their original elevations as possible. In practise this is impossible, either due to the weather or to logistics problems. Consequently, an algorithm must be used to calculate the balance of poles missed in any one year of measurement. In this study this is done through a correlation matrix consisting of all the poles. Lliboutry (1974) has described another, more rigorous technique. In this 'separate component' case two time series are preserved, one relating to melting in summer and the other to accumulation the year round. Each of the two time series relate to different parts of the GCM predictions. Arctic winters are predicted to show a much greater warming than the global average; this will bring increased precipitation (Houghton *et al.*, 1990). Summers will show a more modest warming, but, nonetheless will be associated with a decrease in the area of sea-ice and increased glacier melting.

The Canadian high Arctic glacier data are presented as accumulation and melt time series in Figures 3,4 and 5.

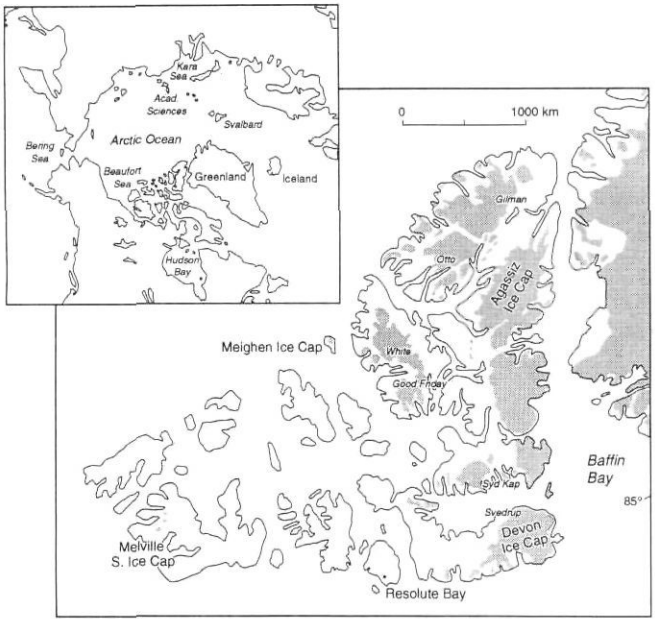

FIGURE 1. Location map, Queen Elizabeth Islands. On the main map, valley glaciers referred to in the text are in small italics, *e.g.*, *Gilman* is Gilman Glacier.

Localisation de l'archipel de la Reine-Élisabeth. Les noms donnés en italique sur la carte principale font référence aux glaciers de vallée dont on parle dans le texte

Without entering into any detailed discussion, one should note that, with the possible exception of the Devon snow accumulation time series, no significant long-term, linear trends are evident in either of the melt or snow accumulation time series. This again can be construed as indicating that the greenhouse effect is not yet evident in the Queen Elizabeth Islands. However, a greenhouse signal may be buried in the noise of natural variability.

ICE CORE RECORDS

A 32-yr record is valuable for monitoring present climate but is still rather short for detecting trends. Ice core data

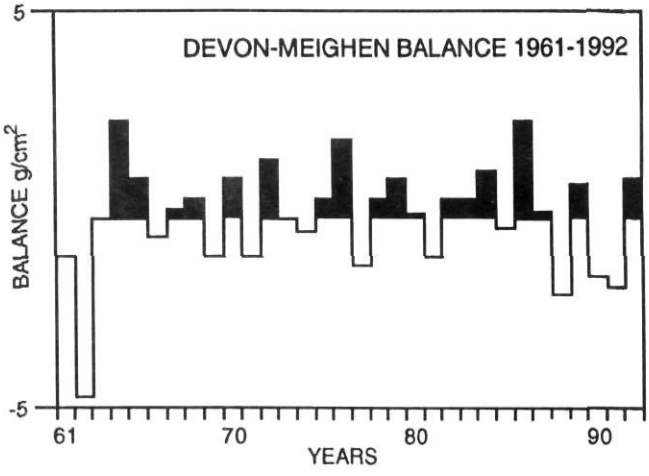

FIGURE 2. Mass balance on Devon and Meighen ice caps. Original values from each ice cap were normalised and summed. Shading is for above average values. Because the balance values are normalised they are relative and not absolute.

Bilan de masse sur les calottes glaciaires Devon et Meighen. Les données d'origine de chacune des calottes ont été normalisées et résumées. La zone tramée est réservée aux valeurs plus élevées que la moyenne. Les valeurs du bilan ayant été normalisées, elles sont relatives et non absolues.

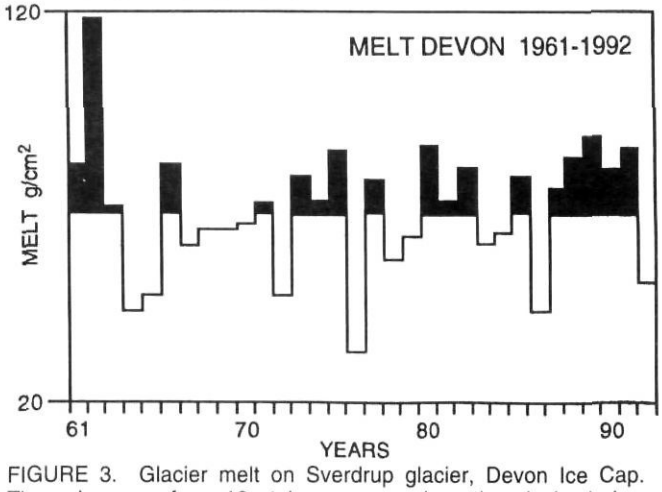

FIGURE 3. Glacier melt on Sverdrup glacier, Devon Ice Cap. The values are from 16 stakes measured on the glacier below 800 m asl. High melt means warm summers. Above average values are shaded.

La fonte sur le glacier Sverdrup, de la calotte glaciaire de Devon. Les valeurs sont fondées sur des mesures prélevées à partir de 16 piquets sous 800 m d'altitude. Une fonte élevée signifie des étés chauds. Les valeurs plus élevées que la moyenne sont tramées.

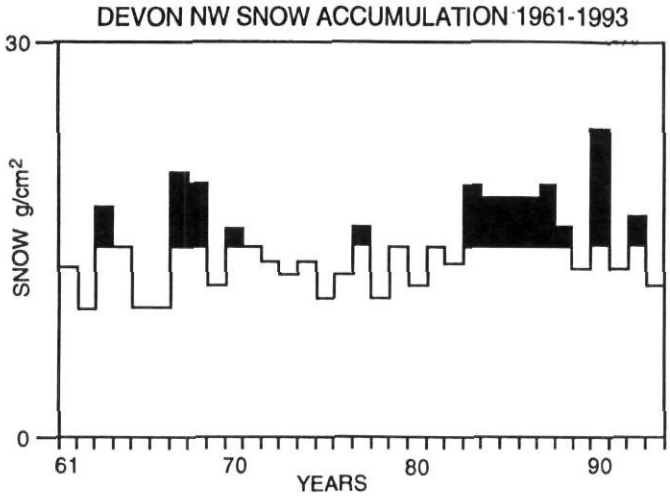

FIGURE 4. Snow accumulation above the firn line (*ca.* 1500 m asl) on the northwest side of Devon Ice Cap for the period 1961-1993. Note: there is a slight tendency for increased accumulation over the 33 year period. The period represented each year is from the time snow accumulation begins (after the melt season ends in August) until the end of June the following year. As the date of measurement varies from year to year, all records are corrected to June 30 on the assumption that snow falls evenly throughout the year. While this assumption is false it is the only way to avoid bias for early, or late, annual measurements which vary from late March in some years to late June in others.

L'accumulation de neige au-dessus de la ligne des arbres (environ 1500 m) sur le côté nord-est de la calotte de Devon, de 1961 à 1993. Note : on observe une légère tendance à une augmentation des accumulations sur une période de 33 ans. À chaque année, la période commence avec les premières accumulations de neige (après la période de fonte qui se termine en août) pour se terminer en juin l'année suivante. La date de mesure variant d'une année à l'autre, tous les relevés sont corrigés au 30 juin, présumant ainsi que les averses de neige sont également réparties tout au long de l'année. Bien que cette présomption soit fausse, c'est la seule façon d'éviter les déviations à partir des mesures hâtives, tardives et annuelles qui peuvent varier de la fin de mars à la fin de juin selon les années.

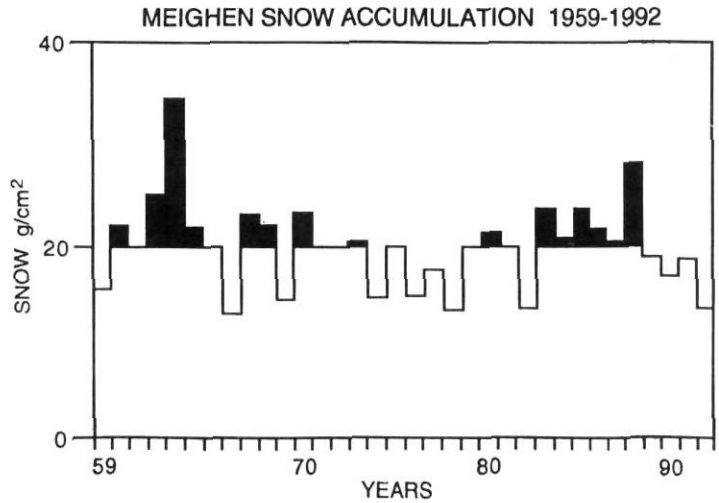

FIGURE 5. Snow accumulation on Meighen Ice Cap for the period 1959-1992. Details as for Figure 4.

L'accumulation de neige sur la calotte de Meighen, de 1959 à 1992. Voir les commentaires de la figure 4.

can be used to extend the record back in time. Ice core stable isotope records (for example δ-^{18}O) serve as proxies for annual temperatures (Dansgaard *et al.*, 1973), and ice layer records for summer temperatures (Koerner, 1977). Stable isotope records have been used extensively in developing paleoclimate records. The best known are from Greenland and Antarctica (*e.g.* Langway *et al.*, 1985; Lorius *et al.*, 1985). The use of ice layers as proxy temperature indicators is less well known. Briefly, ice layers form in subpolar regions of ice caps and ice sheets when the air temperatures rise above freezing. These layers are preserved and present a record of periods of summer melt of varying length back in time.

Figure 6 shows a combined Devon/Agassiz Ice Cap ice layer record covering the past 800 years. The record ends in 1971, 10 years after the mass balance measurements began on Devon and Meighen Ice Caps (1961 and 1959 respectively). The ice core record shows a sharp decrease in melt from the late 1950's to 1971. Part of this change in summer melting is apparent in the heavy melt right at the beginning of the mass balance and melt records changing to less melt after 1962 (Fig. 2). However, the ice core record suggests that the recent (1851-1951) period of melt is the most intense in the 800 year record. The annual temperature record (δ), does not show such a uniqueness. This indicates that summer temperatures have changed more than those in the rest of the year and is in agreement with the conclusions reached from glacier geometry changes mentioned previously.

If the record is extended even further, another picture emerges (Fig. 7). This time the recent warming trend is seen rising from the coldest period of the 10,000 year record. However, neither in terms of δ-values or ice layers is the present century uniquely warm; it could be a part of the natural variability of climate rather than a greenhouse warming effect. In fact, the greater change of summer temperatures compared to annual temperatures in the most recent warming trend runs counter to the GCM prediction of the seasonal response in the high Arctic to Greenhouse warming.

To improve the record further, it is planned to amalgamate all the high Arctic melt and snow accumulation glacier data to provide a circumpolar picture of climate change. In addition, the installation of sophisticated dataloggers, providing year-round records of various meteorological parameters, on some of the ice caps will promote the development of better transfer functions for improved interpretation of ice core records and improved glacier parameterisation input to models. We are presently engaged in such a study in cooperation with industry (Campbell Scientific, Canada). Dataloggers have so far been installed on Agassiz and Devon Ice Caps (Fig. 1), and also on the Academy of Sciences Ice Cap in the Russian Severnaya Zemlya archipelago.

II. POLLUTION RECORDS

Ice cores also contain records of past and present atmospheric chemistry as the accumulating snow traps aero-

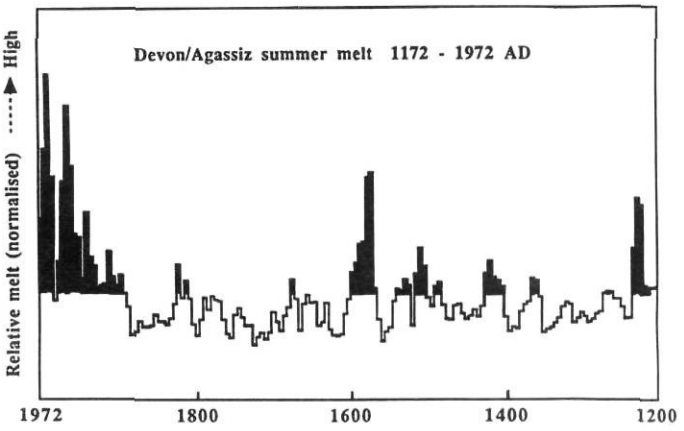

FIGURE 6. Summer melt on Devon and Agassiz Ice Caps from ice core measurements. Values were first normalised and summed to provide a combined record. High melt is measured from a high concentration of ice layers at a particular depth. The measurements were made continuously from both cores.

La fonte estivale aux calottes de Devon et d'Agassiz à partir des mesures de carottes. Les valeurs ont d'abord été normalisées puis résumées afin d'établir un fichier combiné. On mesure une fonte élevée là où il y a une forte concentration de couches de glace à une profondeur donnée. Les mesures ont été faites de façon continue à partir des deux carottes.

sols and air, storing the latter as bubbles in the ice. A major advance in our understanding of the interactions between climate and greenhouse gases has been gained from Antarctic ice cores (Barnola *et al.*, 1987) which show that when temperatures were low during the past glacial period greenhouse gases were also at low concentrations in the atmosphere. In addition, the same cores and others (*e.g.* Dansgaard *et al.*, 1985) show that atmospheric turbidity varied inversely with temperature during the last glacial period.

Measurements in Canadian high Arctic ice cores were the first to show a rapid increase in acidity of snow beginning in the 1950's (Koerner and Fisher, 1982; Barrie *et al.*, 1985). This record was substantiated by a 45-year record of the solar extinction coefficient from Franz Josef Land (Marshunova and Radionov, 1991). The change in this coefficient is largely due to changing aerosol concentrations in the atmosphere on the Eurasian side of the Arctic Ocean, and it too shows large increases in the early 1950's. More detailed records of industrial pollutants from Greenland (Neftel *et al.*, 1985, Mayewski *et al.*, 1986) show the same increase and attribute the increased acidity to sulphates and nitrates, the increase beginning early in the last century.

This is important in terms of present-day climate change as aerosols, particularly those composed of sulphates, have a cooling effect on climate globally (Lelieveld and Heintzenberg, 1992). This effect is counteracting that of anthropogenic greenhouse gases and further complicating the modelling of future climate (Slinn, 1991). However, modelling the effect of aerosols on climatic change in the Arctic indicates that when increased levels of soot aerosol are included, they outweigh the effect of sulphate cooling to

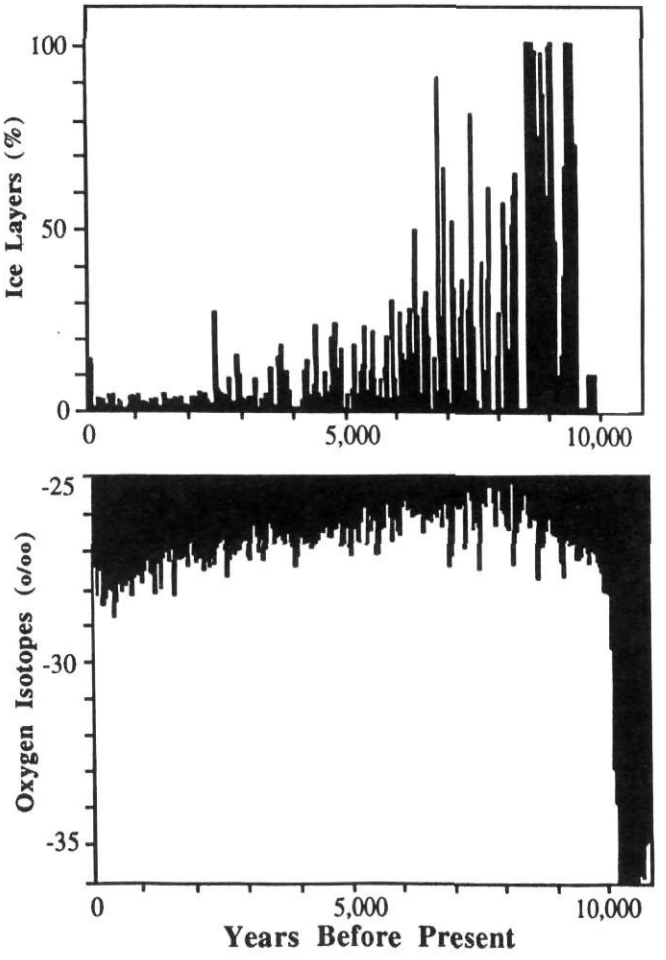

FIGURE 7. Melt and stable isotope records from Agassiz Ice Cap, Northern Ellesmere Island between 1972 (0) and the glacial/interglacial transition period (11,500 BP). Ice layers are expressed as a percentage of the annual accumulation layer. Thus 100% means the entire annual snow layer was converted by melting when at the surface during the summer.

La fonte et les données des isotopes stables de la calotte d'Agassiz, dans le nord de l'île d'Ellesmere, entre 1972 (0) et la période de transition glaciaire-interglaciaire (11 500 BP). Les couches de glace sont exprimées en pourcentage de la couche d'accumulation annuelle. Ainsi, 100 % veut dire que la couche annuelle totale de neige a été transformée par la fonte durant l'été lorsqu'elle est en surface.

effect an overall warming which adds to that due to greenhouse gases (Blanchet, 1991).

Originally, it was speculated that the lack of evidence for climate change inferred from glacier measurements over the past thirty years was due to the equal, but opposite effects of greenhouse warming and aerosol cooling (Koerner, 1992). The argument was appealing as down-turn from the 100-year warming between 1850 and 1950 in the circumpolar record occurs close to the time when anthropogenic aerosols increased sharply. However, if Blanchet's model is correct there should be an *increased* anthropogenic warming when both the greenhouse gas and overall aerosol effects complement each other. The lack of a warming trend then becomes increasingly puzzling. Further investigation of the complete anthropogenic effect is clearly warranted,

especially with a view to incorporation of the aerosol effect into the GCM's.

CONCLUSIONS

The study and monitoring of glaciers is an essential component of the overall study of climate change. Variations of accumulation and ablation rates on glaciers allow climate to be monitored in areas where instrumental records are sparse. Incorporation of modern datalogger techniques into the glacier balance network areas are improving transfer functions used in the interpretation of ice core records. The ice core records from the Canadian Arctic, which cover a complete glacial cycle, place the warming over the last 100 years in its true perspective in terms of 1000-, 10,000- and even 100,000-year time frames. No unique character can be assigned to the warming trend over the last 100 years in the high Arctic. This would suggest the trend is part of the natural variability of climate rather than due to anthropogenic effects. Furthermore, no significant trend has been found over the past 32 years in winter snow accumulation or summer melt on Canadian Arctic glaciers despite the possible combined warming effect of increasing concentrations of greenhouse gases and aerosols in the atmosphere.

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