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THE DISTRIBUTION OF 10 m TEMPERATURES ON THE ROSS ICE SHELF

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Abstract. Ten-meter temperatures on the Ross Ice Shelf increased by 1 deg between 1958 and 1974. Surface temperatures at the "Byrd" and McMurdo stations have also risen during this period and the observed change is consistent with the 10 m temperature increase. This rising trend in temperature appears to have an anti-phase relationship with northern hemisphere cooling.

Résumé. *La distribution des températures sur les dix premiers mètres du Ross Ice Shelf.* Les températures sur les dix premiers mètres du Ross Ice Shelf se sont accrues de 1 deg entre 1958 et 1974. Les températures de surface aux stations "Byrd" et McMurdo ont aussi augmenté pendant cette période, et les changements observés sont cohérents avec l'accroissement de température sur dix mètres. Cette tendance au réchauffement semble avoir un lien de compensation avec un refroidissement dans l'hémisphère Sud.

Zusammenfassung. *Die Verteilung der Temperatur in 10 m Tiefe auf dem Ross Ice Shelf.* Die Temperatur in 10 m Tiefe ist auf dem Ross-Schelfeis zwischen 1958 und 1974 um 1 deg angestiegen. Auch die Oberflächentemperaturen an der "Byrd"-Station und bei McMurdo sind in dieser Periode gestiegen und die beobachteten Änderungen stimmen mit dem Anstieg in 10 m Tiefe überein. Diese Erwärmungstendenz scheint mit der Abkühlung auf der nördlichen Hemisphäre in einer gegensätzlichen Beziehung zu stehen.

Ten-meter temperatures were measured over large areas of the Ross Ice Shelf during the International Geophysical Year of 1957–58 (Crary and others, 1962) and in 1973–75 as part of the Ross Ice Shelf Project (RISP). Comparison of the results reveals a consistent temperature increase over a large area of the eastern Ross Ice Shelf. In section 1 I describe the measurements and present the results, and in section 2 I discuss possible surface-temperature changes that could have caused the observed increase.

1. Observations and results

During the austral summers 1973–74 and 1974–75 geophysical and glaciological measurements were made at a network of stations 50 km apart over the eastern half of the Ross Ice Shelf (reported in the July 1974 issue of *Antarctic Journal of the United States*). This program forms part of the RISP and similar measurements are planned for the remainder of the ice shelf.

At a selection of the stations, firn cores were collected by J. Nielsen of the University of Copenhagen, and 10 m temperatures were measured using a glass-bead thermistor with a d.c. Wheatstone bridge. Positions of these stations are shown in Figure 1. Convective air flow near the bottom of each hole was minimized by means of a polystyrene disk mounted above the thermistor so that it loosely plugged the hole. The thermistor usually remained down hole for at least one hour and often for several hours. After an initial settling period of 10 to 15 min, frequent resistance measurements were made and the corresponding temperatures were found to follow Newton's law of cooling closely. A semilogarithmic plot of the cooling curve was made for each set of measurements to give the equilibrium 10 m temperature. Measurements with different thermistors down the same hole, and with the same thermistor down adjacent holes, showed agreement to less than 0.1 deg.

At 10 m depth in the firn of Little America and Maudheim the annual temperature cycle has an amplitude of 0.4 deg with a phase lag of about seven months (Crary and others, 1962, p. 122). Assuming these values to be typical of the entire Ross Ice Shelf, the measured 10 m temperatures were corrected to corresponding annual averages. The resultant values are assumed to be accurate to ± 0.2 deg.

Figure 1 shows individual plots of 10 m isotherms for both the I.G.Y. and the RISP measurements, with assigned epochs of 1958 and 1974 respectively. The 1974 isotherms form a pattern that is broadly similar to that deduced by Crary and others (1962) from the 1958 measurements. However, over most of the region, the temperatures have increased during the 16 year interval by approximately 1 deg.

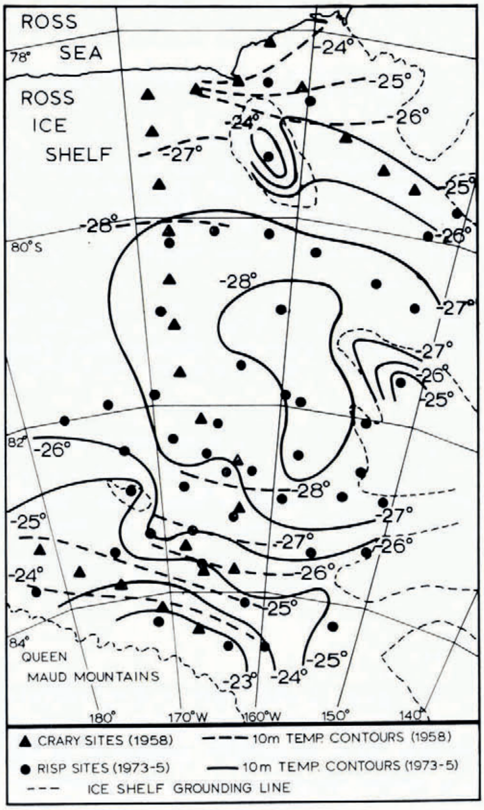

Fig. 1. The eastern half of the Ross Ice Shelf showing 10 m isotherms for 1958 and 1974 and the positions where 10 m temperatures were measured.

2. Interpretation

Ten-meter temperatures are representative, approximately, of the surface air temperature averaged over several years. Consequently, we may interpret the observed 1 deg increase as a change in average air temperatures. Figure 2 shows the variations in the annual mean temperature at the "Byrd" and McMurdo stations for the period 1957–73. It was compiled from data in Budd (1975), where the temperature deviations at "Byrd" and McMurdo are plotted independently, and clearly follow very similar trends. Thus we might expect that temperatures over the Ross Ice Shelf, lying midway between "Byrd" and McMurdo, will follow the same trends, which may be approximated as a roughly cyclic variation superimposed on a warming of about 0.2 deg per year. This pattern shows good agreement with that deduced by Orheim (1972) for temperatures at Deception Island off the west coast of the Antarctic Peninsula.

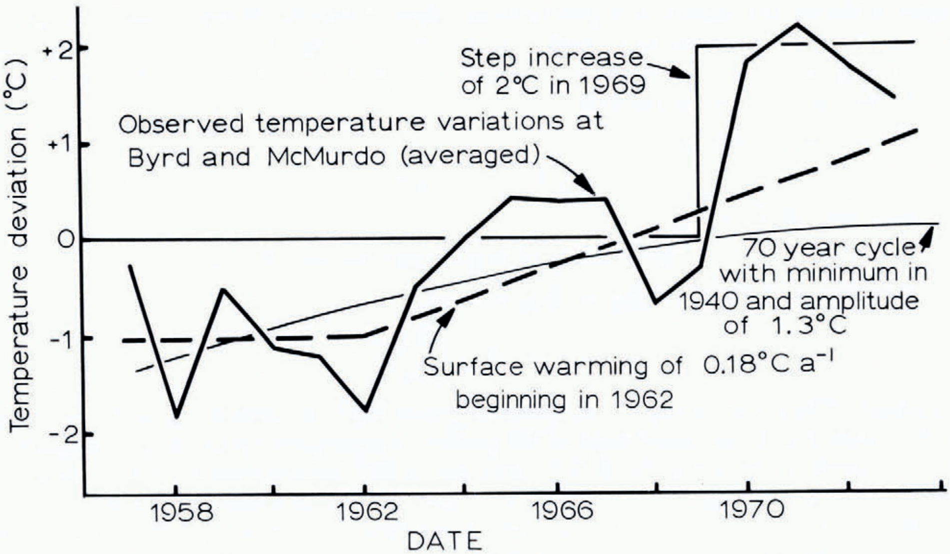

Fig. 2. Surface temperatures at "Byrd" and McMurdo stations expressed as deviations from the 1957–73 averages. The lines showing warming since 1962, part of a 70 year cycle, and a step increase in 1969, illustrate possible causes for the observed 1 deg increase in 10 m temperatures.

In order to estimate the magnitude of the changes in annual mean surface temperature θ_s necessary to produce the observed 1 deg increase in the 10 m temperatures I shall separately consider:

(i) a steady increase in θ_s since some time t_0,
(ii) a cyclic variation of θ_s,
(iii) a step change in θ_s.

The calculations neglect the effects of snow accumulation. This approximation leads to an over-estimation of surface temperature changes necessary to produce the observed 1 deg increase. However, since the accumulation rates over most of the region are less than 10 cm of water per year (Clausen and Dansgaard, in press), the errors introduced by the approximation are less than those involved in the temperature measurement. To take account of the depth gradient of thermal diffusivity, the top 10 m of firn are considered as a pile of 1 m thick layers each with a different density. The response to the annual surface temperature cycle is solved for each layer and excellent agreement is obtained with the observed phase lag and amplitude decay in the upper 10 m of firn at Little America if we adopt a relationship between thermal conductivity and firn density that is almost identical to that proposed by Yen (1965).

(i) for

$$\theta_s(t) = \theta_0 + \alpha(t - t_0)$$

where α is a constant and t is time, the relevant equation for the temperature at depth z in the firn is

$$\theta_z(t) = \theta_0 + 4\alpha(t - t_0) i^2 \operatorname{erfc}\left(\frac{z}{2[\kappa(t-t_0)]^{\frac{1}{2}}}\right) \tag{1}$$

(Carslaw and Jaeger, 1959, p. 63) where κ is the thermal diffusivity and where

$$4i^2 \operatorname{erfc} x = \left[(1+2x^2) \operatorname{erfc} x - \frac{2}{\sqrt{\pi}} x \exp(-x^2)\right]$$

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Figure 2 shows the surface temperatures at "Byrd" and McMurdo starting to increase in 1962 so $(t-t_0) \approx 12$ years and, with $(\theta_{10}(t)-\theta_0) \approx 1$ deg, Equation (1) was solved to give a warming rate of $\alpha \approx 0.18$ deg a^{-1}. This is included in Figure 2 and shows good agreement with the observed temperatures.

(ii) For cyclic variations in θ_s

$$\theta_s(t) = \theta_0+A \cos (\omega t-\epsilon)$$

with period $T = 2\pi/\omega$,

$$\theta_z(t) = \theta_0+A \exp (-\beta z) \cos (\omega t-\beta z-\epsilon) \tag{2}$$

(Carslaw and Jaeger, 1959, p. 64), where

$$\beta = \left(\frac{\omega}{2\kappa}\right)^{\frac{1}{2}}.$$

The amplitude diminishes as $\exp (-\beta z)$ and the phase lag is βz radians. In order to estimate minimum values for A, the amplitude of the surface temperature variations, we assume that the 16 year interval between the I.G.Y. and the RISP measurements represents an odd number of half wave lengths, with 10 m temperatures in 1958 at a minimum and in 1974 at a maximum. Thus $(2n+1)T/2 = 16$ years and Equation (2) has been solved with n taking integral values between 0 and 4. The corresponding values of A are plotted against T in Figure 3. For periods greater than 32 years the 1958 ten-meter temperature is assumed to represent a minimum and the graph becomes continuous.

The surface temperature variations shown in Figure 2 have a period of between 6 and 11 years with amplitudes that are somewhat smaller than calculated from Equation (2): 2.3 deg for $T \approx 6$ years and 1.6 deg for $T \approx 11$ years. Furthermore the 1958 observed minimum in surface temperature is two years out of phase with that required for a 1958 minimum 10 m temperature.

A 32 year cycle requires only 1 deg amplitude at the surface, and the observations displayed in Figure 2 could represent part of such a cycle. However, observations from Deception

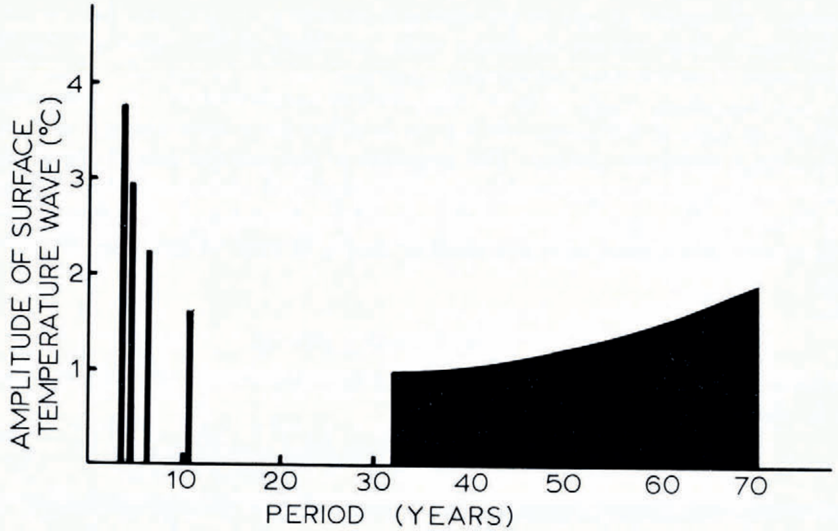

Fig. 3. The amplitude of cyclic surface temperature variations that could result in the observed 10 m warming plotted against the period.

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Island (Orheim, 1972) and from the northern hemisphere (Dansgaard and others, 1975) do not show a near 30 year dominant period. Instead they both display temperature cycles having an approximately 70 year period with a northern hemisphere maximum and southern hemisphere minimum in about 1940. Assuming the Deception Island records to be typical of Antarctic conditions, implying a 10 m temperature minimum in 1945, the amplitude of the surface temperature cycle appropriate to the Ross Ice Shelf observations is $A = 1.3$ deg. This is plotted in Figure 2 and can be seen to be easily within the observed trend.

(iii) In 1969–70 the temperatures at McMurdo and "Byrd" sharply increased by about 2 deg. The response of firn temperatures to a step change in surface temperature from θ_0 to θ_1 is expressed by

$$\theta_z(t) = \theta_0 + (\theta_1 - \theta_0) \operatorname{erfc}\left(\frac{z}{2[\kappa(t-t_0)]^{\frac{1}{2}}}\right) \tag{3}$$

(Carslaw and Jaeger, 1959, p. 63), if, for a long time prior to t_0, the surface temperature was θ_0. Clearly this is not the case at "Byrd" and McMurdo where there is a rising trend in temperature, and the effect of the assumption is to overestimate the magnitude of the step increase.

Equation (3) can be written

$$\frac{\Delta\theta_z}{\Delta\theta_s} = \operatorname{erfc}\left\{\frac{z}{2(\kappa\,\Delta t)^{\frac{1}{2}}}\right\} \tag{4}$$

where $\Delta\theta_z = \theta_z(t) - \theta_0$, $\Delta\theta_s = \theta_1 - \theta_0$, $\Delta t = t - t_0$.

Equation (4) was solved to give $\Delta\theta_{10}/\Delta\theta_s$ for $\Delta t = 0 \rightarrow 50$ years as shown in Figure 4. Figure 4 is used to calculate the magnitude of the step increase $\Delta\theta_s$ in surface temperature taking place during the period $1950 \leqslant t_0 \leqslant 1972$, and the results are plotted in Figure 5. There is a rapid increase in $\Delta\theta_s$ for $t_0 < 1958$ and for $t_0 > 1970$. The observed step-like increase in θ_s shown in Figure 2 took place in 1969 when, from Figure 5, $\Delta\theta_s \approx 2$ deg, and this shows good agreement with the magnitude of the observed increase.

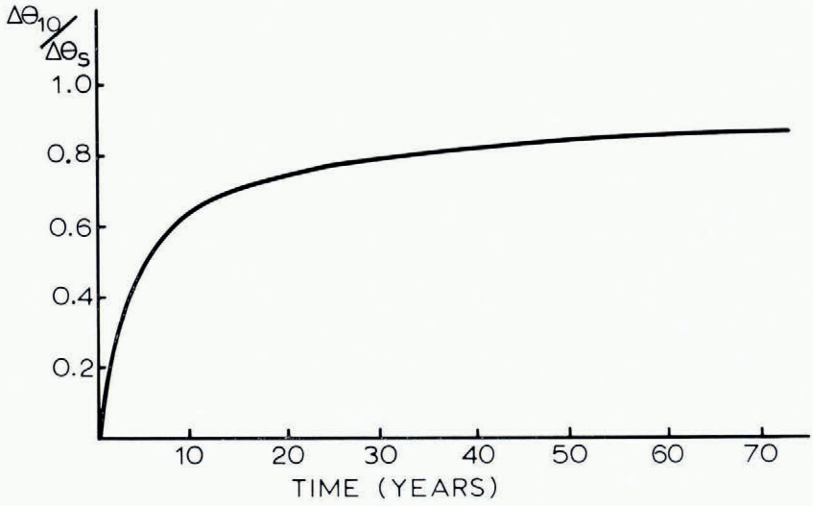

Fig. 4. The temperature response at 10 m depth ($\Delta\theta_{10}$) to a step increase ($\Delta\theta_s$) in surface temperature plotted against time.

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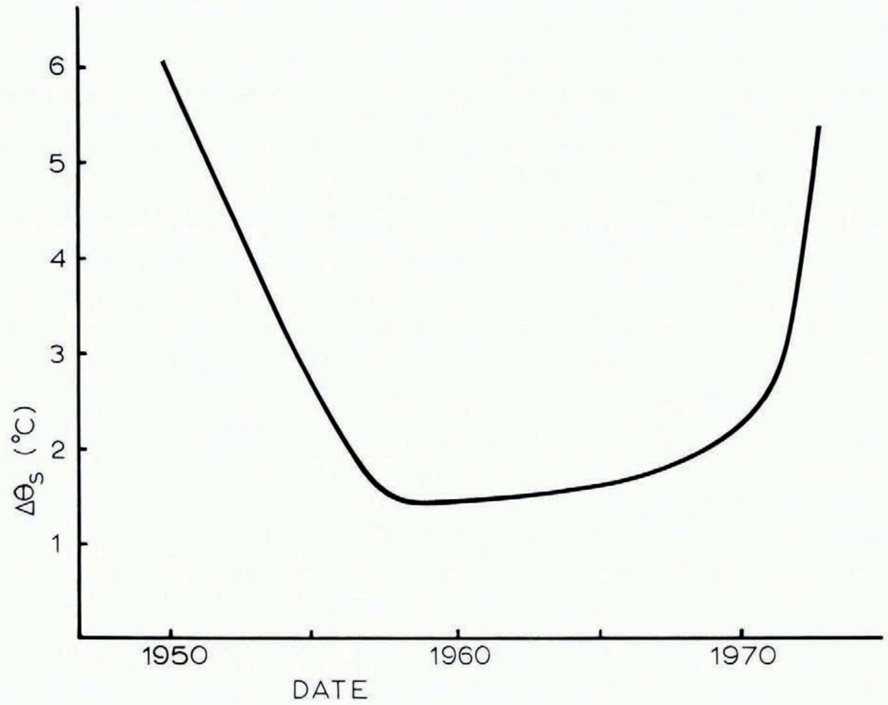

Fig. 5. The step increase ($\Delta\theta_s$) in surface temperature necessary to produce a 10 m warming of 1 deg between 1958 and 1974 plotted against date of increase.

3. Conclusions

The 1 deg rise in Ross Ice Shelf 10 m temperatures between 1958 and 1974 can be explained by any of these mechanisms:

(i) A steady surface warming since 1962 of 0.18 deg a^{-1}.

(ii) Cyclic variations in surface temperature with periods of 6, 11, 32 and 70 years and having their respective maxima in 1972, 1972, 1970 and 1975. Records from elsewhere favor the 11 and 70 year cycles.

(iii) A 1969 step increase in surface temperature of 2 deg.

Surface temperature measurements at "Byrd" and McMurdo stations display a general warming since 1958 with a step-like increase in 1969–70 and the magnitude of these changes is sufficient to explain the observed increase in Ross Ice Shelf 10 m temperatures. However, the observation period at "Byrd" and McMurdo is too short to indicate whether the observed warming is part of a long-period cyclic change. Accurate temperature measurements in the upper 100 m of ice shelf may help to solve this problem, and temperatures in a 100 m hole at lat. 82° 22′ S., long. 168° 40′ W. were measured by John Rand of the Cold Regions Research and Engineering Laboratory during December 1974. Unfortunately, at the time of writing, the results are not available. Oxygen isotope analysis of ice from the 100 m bore hole should reveal major temperature changes that have occurred during the last 800 years.

The evidence for warming in the Ross Ice Shelf area provided by the 10 m temperature increase and by the observations at "Byrd" and McMurdo is consistent with evidence from Deception Island off the west coast of the Antarctic Peninsula. The reconstructed surface temperature history at Deception Island (Orheim, 1972) has a 70 year cycle that is 180° out of phase with a similar temperature cycle deduced from oxygen-isotope analysis of Greenland ice cores (Dansgaard and others, 1975). This antiphase relationship between northern and southern hemisphere temperature records provides support for Fletcher's (1972) suggestion that increased sea ice around Antarctica should lead to increased vigour of atmospheric circulation, a northward shifting of the meteorological equator, and warming in the northern hemisphere.

ACKNOWLEDGEMENTS

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DISCUSSION

W. S. B. PATERSON: Does the 70-year cycle show in the "Byrd" or Little America oxygen isotope profiles?

R. H. THOMAS: The near-surface "Byrd" cores have only recently been recovered and have not yet been analysed, and the results from the Little America cores have not been published.

W. F. BUDD: Do you think you would obtain the observed 10 m temperature difference if you used as input to the heat conduction equation the observed annual mean temperature record that you presented?

THOMAS: I think we would get slightly more than the observed difference.

PATERSON: Is there any melting in summer on the Ross Ice Shelf?

THOMAS: There is virtually no melting and pits reveal only very thin ice layers.

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